Irradiation Opens up Third Film Dimension

Electron Irradiation. In several aspects, films made of technical thermoplastics for flexible and molded interconnect devices must comply with a requirement profile that they have been unable to fulfill so far. Now, it has been shown that films cross-linked by irradiation meet these demands.

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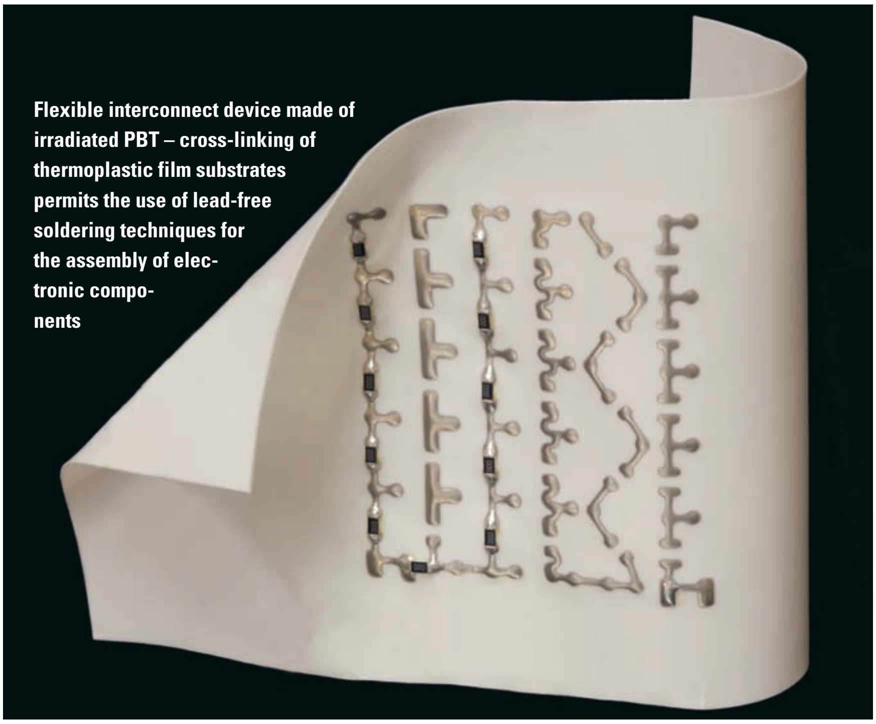
Polyimide (PI), polyethylene terephthalate (PET), and polyethylene naphthalate (PEN) are typical substrate materials used today for integrated flexible circuits in electronic applications. Hereby, PI film is practically the only material that can be processed in lead-free reflow soldering installations [1], as its excellent thermal properties fulfill one of the most important requirements: it is solder resistant. On the other hand, PI is also a relatively expensive base material for flexible flat cables (FFC) and flexible printed circuits (FPC). A replacement with substrates based on technical thermoplastics would be highly advantageous, but so far, their thermal application limits are inadequate for lead-free soldering processes.

One possibility of qualifying technical plastic substrates for these applications is cross-linking by means of irradiation. Hereby, the recombination of radiation-induced radicals leads to the formation of a three-dimensional network of macromolecules, which considerably increases the short-term temperature resistance, thereby extending the thermal application limits of thermoplastics [2, 3]. In order to be competitive in terms of material characteristics, radiation cross-linkable alternative materials must feature the following properties, which are exhibited by PI films during production and use of flexible interconnect devices:

- Soldering resistance at short-term temperatures above 250 °C during convection reflow soldering,
- geometric fidelity and flatness of the films for fault-free processing in the process chain, e.g. during assembly and termination work,
- low thermal expansion to prevent e.g. fractures in circuit tracks and soldered joints, but also to maintain dimensional accuracy of the circuit layout,
- mechanical flexibility (isotropic stiffness and strength), and reliable metallization adherence.


Flexible interconnect device made of irradiated PBT – cross-linking of thermoplastic film substrates permits the use of lead-free soldering techniques for the assembly of electronic components

Integration of Flexible Films in 3-D MIDs

Moreover, in the course of the increasing integration of electronic modules in decentralized functional units, flexible thermoplastic films also offer potentials for the manufacture of novel injection molded interconnect devices, so-called 3-D MIDs. Hereby, thermoplastic film substrates eliminate the need for elaborate three-dimensional metallizing processes. In future, this would enable flexible films to be metallized and structured two-dimensionally – e.g. by means of hot embossing – followed by three-dimensional forming and full-surface back injection. Due to the low extensibility of the copper circuit tracks, the three-dimensional deformability of flexible thermoplastic films is limited [4]. Also the implementation of flex-rigid composites in MID components is possible by introducing selective gaps during back injection of the film insert.

When using irradiated plastic films as substrates for flexible interconnect devices or for manufacturing MID components, the exact moment at which irradiation is optimally done in the process

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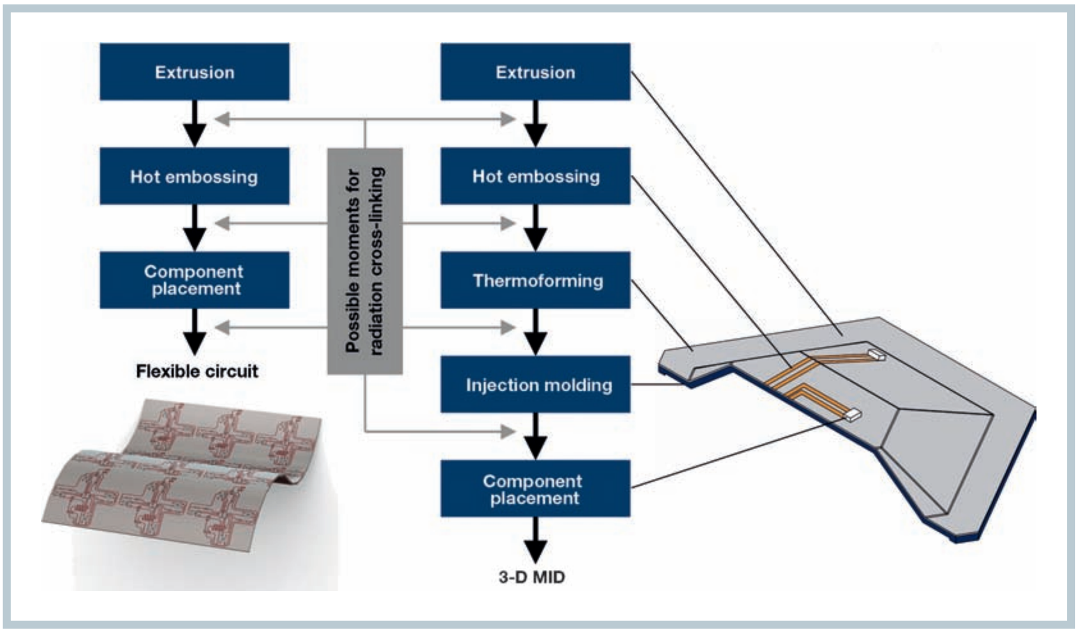

Fig. 1. Process chains for manufacturing flexible circuits and 3-D MIDs using radiation cross-linked films, with possible moments for irradiation

chain is decisive for processing quality and usability **(Fig. 1)**. Apart from the requirements mentioned above for flexible interconnect devices, other important criteria during the manufacture of MIDs are three-dimensional deformability, and the film's bonding with the injection molding substrate.

Films Made of Radiation Cross-linkable PA and PBT

For investigations into the manufacture of flexible interconnect devices based on radiation cross-linkable films, polyamide 12 (PA12) and polybutylene terephthalate (PBT) were extruded into films **(Table 1)** in a laboratory installation (manufacturer: Dr. Collin in Ebersberg, Germany) by means of the chill-roll process. Both materials are commercially available, radiation cross-linkable types of thermoplastic (manufacturer: PTS Plastics Technologie Service Marketing- und Vertriebs-GmbH in Adelshofen, Germany).

Electron irradiation of the films was carried out by BGS Beta Gamma Service GmbH & Co. KG in Saal, Germany, with a dose of 66 kGy for PA12, and 165 kGy for PBT in accordance with manufacturer specifications. The degree of cross-linking of the PA12 film was determined at 53 % by means of gel value analysis. Due to the lack of a non-hazardous solvent, determination of the degree of cross-linking of PBT films was not carried out.

Material Description		PA12 V-Rilsan-PA12-AECN 0 TL	PBT V-PTS-Createc B3HZC
Film thickness	[µm]	300	350
Die temperature	[°C]	250	250
Chill roll temperature	[°C]	90	80
Extruder speed	[min^{-1}]	75	75
Haul-off speed	[m/min]	2.4	1.8

Table 1. Investigated radiation cross-linkable materials and process parameters for film production

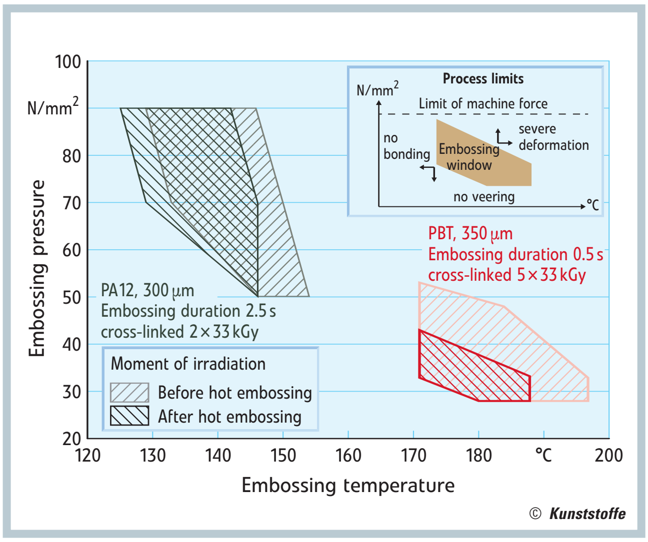

Fig. 2. Influence of embossing temperature and embossing pressure as well as the moment of irradiation on the metallizability of PA12 and PBT film with an 18 µm thin, black oxidized copper embossing foil

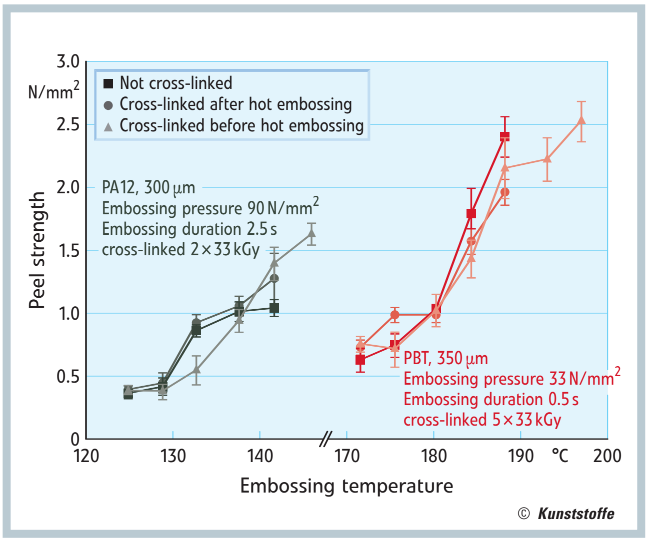

Fig. 3. Influence of embossing die temperature and the moment of irradiation on the peel strength of the metallization for PA12 and PBT film with an 18 µm thin, black oxidized copper embossing foil

Hot Embossing – Smooth Metallization of Flexible Films

Regarding metallization and structuring of the film substrate with circuit tracks, and the required optimum moment for irradiation, the hot embossing process was investigated in process studies. Irradiation prior to metallizing increases the resistance to thermal distortion of PBT and PA12 films. Consequently, higher loads can be applied during hot embossing, with simultaneous minimum distortion **(Fig. 2)**. Hereby, the bonding strength of copper tracks on plastic films is determined mainly by the embossing temperature, as shown by peel strength tests. A significant influence of the irradiation moment on bonding strength could not be determined **(Fig. 3)**. In fact, the sequence of irradiation and hot embossing is significant for the deformation of the plastic/metal bond. With identical process parameters and comparable bonding strength, films irradiated prior to hot stamping exhibit a considerably lower deformation without a significant bulge formation **(Fig. 4)**. The increased stiffness of irradiated films close to the crystallite melting point – which is about 225 °C for the examined PBT – counteracts the plastic deformation under high mechanical load (embossing pressure) and reduces the formation of embossing bulges.

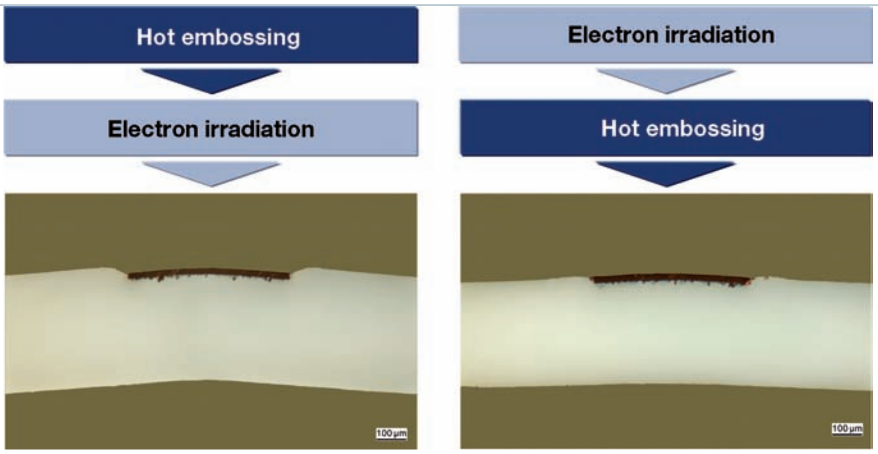

Fig. 4. Influence of the processing sequence of metallization and irradiation (5 × 33 kGy) on film deformation, based on the example of PBT film with simultaneous adjustment of the process parameters (T = 174°C, t = 0.5 s, and p = 33 N/mm^2)

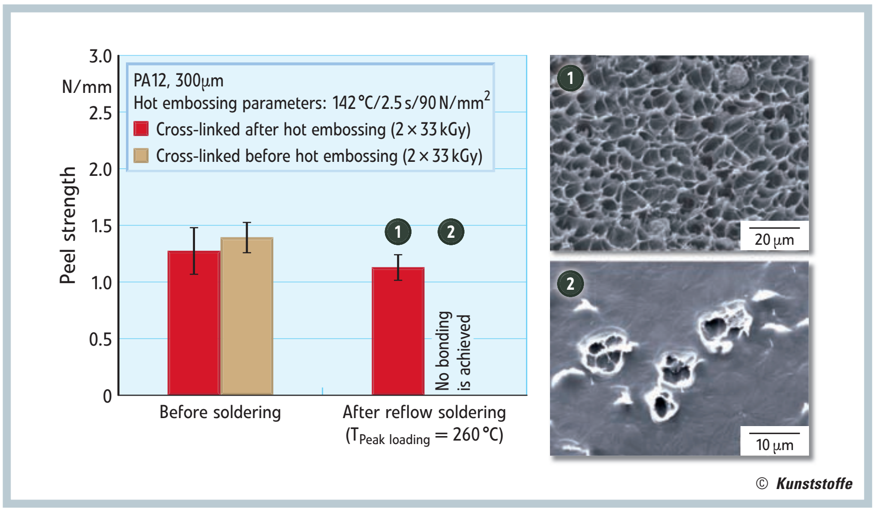

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Fig. 5. Influence of the moment of irradiation on peel strength of the metallization after lead-free reflow soldering, based on the example of PA12 film

Although the moment of irradiation is not important for hot stamping and the metallization bond, it can be decisive for subsequent processing. This is shown by tests with PA12 films in a reflow soldering oven. If the metallization is removed from PA12 films that were irradiated after hot stamping, the surface is marked with pitting and copper inclusions. Opposed to this, the surface is extremely smooth if the irradiation/embossing sequence is reversed **(Fig. 5)**. Here, isolated spherulites of the polyamide can be seen, which can impair the metallization bond to such an extent that the bonding strength is practically zero.

Component Assembly – Extreme Stresses during Soldering Process

Component assembly trials were carried out with PA12 and PBT films in a conventional SMT process chain (solder paste application, component placement, soldering) in order to determine the soldering resistance of irradiated and non-irradiat-

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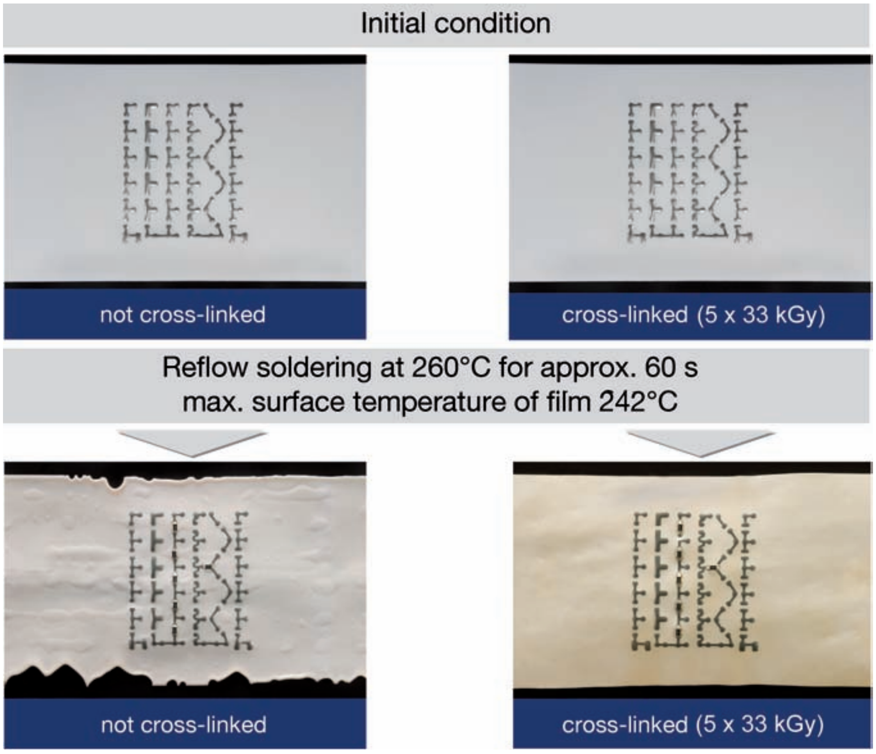
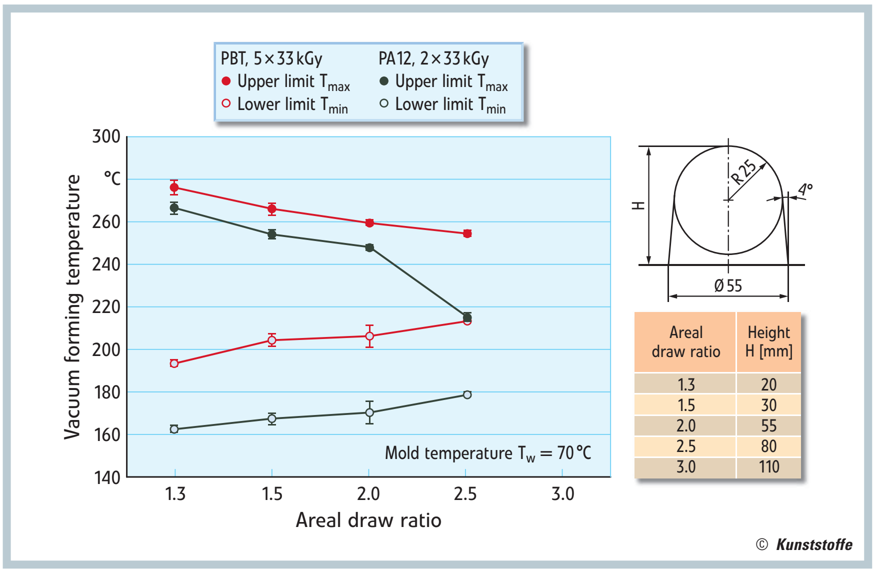


Fig. 6. Results of soldering tests for component assembly on metallized PBT films



Areal draw ratio	Height H [mm]
1.3	20
1.5	30
2.0	55
2.5	80
3.0	110

Fig. 7. Processing temperature limits for vacuum thermoforming of irradiated PA12 and PBT films

ed substrates. A soldering profile with a peak temperature of 260 °C was selected in a convection soldering oven to ensure complete melting of the lead-free SnAgCu solder. As opposed to its non-irradiated counterpart, the irradiated film is soldering resistant **(Fig. 6)**. Comparable results were obtained with PA12 films, so that processing of irradiated flexible films in a standard SMT assembly line is possible.

Thermoforming – the Step into the Third Dimension

In a further processing step, irradiated film circuits can also be used as inserts for the production of 3-D MIDs using back injection. For this, the flexible films (complete with the printed circuit) must be pre-shaped to the component contour of the MID, thus forming its outer envelope at a later stage.

To determine the influence that the moment of irradiation has on the thermoformability of the film substrates, systematic process studies were conducted in a vacuum forming machine (type: Berg mini M3, manufacturer: Peter A. Berg GmbH in Berlin, Germany). **Figure 7** shows the temperature range within which complete impressions of different test geometries are possible for films that were irradiated prior to thermoforming. Hereby, a highly detailed impression of the mold was used to assess the lower limit of the vacuum forming temperature, and the start of fracturing in the component was used to determine the upper limit.

The lower limit of the vacuum forming temperature increases with the areal draw ratio, whereas the upper limit is reduced. The reason for this is that more elongation is required to obtain an impression with higher draw ratios. However, during the vacuum forming process only the atmospheric pressure affects the film. Therefore, the film must exhibit a lower stiffness to obtain higher elongations, which in turn requires higher film temperatures. Presumably, the reduction of the upper limit is the result of the thermo-oxidative degradation during heating up, leading to a reduction of the elongation at break.

The results show that irradiated films are easily formable. Contrary to this, satisfactory forming could not be obtained with non-irradiated films, as they cannot be heated up to the crystallite melting temperature T_m. The stiffness of these films is too low, so that they are destroyed as a result of the high sagging during thermoforming. Irradiated films on the other hand, can also be heated above T_m, as the cross-linking points between the macromolecules lead to a rubber-elastic behavior. In this way, highly detailed components can also be manufactured with higher draw ratios. Of course, in addition to the film's behavior during thermoforming, the influence of metallization must also be taken into account – an aspect that is currently being investigated.

Back Molding – Strength and Functional Integration

To investigate the influence that the moment of irradiation has when back molding the films in an injection molding machine (type: Engel ES 330H / 200V / 80 HL), a plate-shaped geometry was selected. Hereby, the influences of injection speed, melt and mold temperatures, and the moment of irradiation were determined for the bonding strength between PBT film and the back molding substrate. The statistical evaluation shows that the melt and mold temperatures as well as the moment of irradiation are highly significant for bonding strength **(Fig. 8)**. A higher melt temperature reduces melt viscosity, which can lead to better cross-linking. The resulting larger contact surface can contribute to higher bonding strength. Moreover, higher melt and mold temperatures increase molecular mobility within the melt and the film, which improves the probability of entanglements forming between the film and substrate molecules. Due to the covalent links between the polymer chains, irradiation hinders molecular mobility,

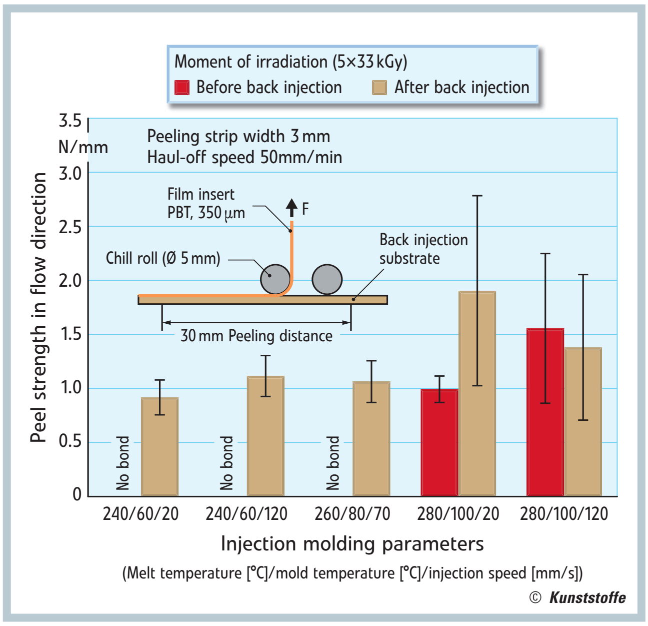


Fig. 8. Bonding strength between PBT film and back injection substrate as a function of injection molding parameters and the moment of irradiation (back injection material: PBT V-PTS-Createc B3HZC)

whereby cross-linking prior to back molding leads to a reduction of bonding strength.

Conclusions

For the manufacture of radiation cross-linked flexible interconnect devices, the question arises regarding the optimum moment for irradiating the thermoplastic film within the processing chain. The results of investigations conducted for PBT show that irradiation should occur between the extrusion and metallizing steps. For PA12, advantages were found for irradiation after metallization.

When metallizing and shaping the plastic films using the hot embossing process, the moment of irradiation is hardly significant for the obtainable bonding strength. However, the results obtained with PA12 showed that an adequate temperature resistance of the plastic/metal bond for the subsequent soldering process can only be ensured if electron irradiation is carried out after the metallization process. The soldering resistance of the cross-linked plastic film is then given.

For the subsequent manufacture of MIDs from the metallized film substrates by means of full-surface back injection, electron irradiation has a very large influence on the thermo-formability of the investigated materials. Thermoforming of non-irradiated films was not possible, whereas semi-finished products of irradiated PA12 and PBT exhibit an outstandingly large window for processing temperatures. Therefore, the films must be irradiated prior to thermoforming. For the subsequent injection molding process, good bonding strength is also obtainable with irradiated films. ■

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