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The Effect of Laser Power, Traverse Velocity and Spot Size on the Peel Resistance of a Polypropylene/Adhesive Bond

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The mean peel resistance force achieved with respect to variation in the laser power, incident spot traverse velocity and incident spot diameter between linear low density polyethylene film backed by a thin commercial adhesive coating that were bonded to a polypropylene (PP) substrate via thermal activation provided by a 27W CO_2 laser is discussed in this work.

The results gathered for this work have been used to generate a novel empirical tool that predicts the CO_2 laser power required to achieve a viable adhesive bond for this material combination. This predictive tool will enable the packaging industry to achieve markedly increased financial yield, process efficiency, reduced material waste and process flexibility.

A laser spot size-dependent linear increase in laser line energy was necessary for this material combination, suggesting the minimal impact of thermal strain rate. Moreover, a high level of repeatability around this threshold laser line energy was indicated, suggesting that laser-activated adhesive bonding of such polymer films is viable.

The adhesion between the material combination trialled here responded linearly to thermal load. In particular, when using the smallest diameter laser spot, it is proposed that the resulting high irradiance caused film or adhesive material damage, thus resulting in reduced peel resistance force.

The experimental work conducted indicated that the processing window of an incident CO_2 laser spot increases with respect to spot diameter, simultaneously yielding greater bond stability in the face of short-term laser variance. © 2015 The Authors. *Packaging Technology and Science* published by John Wiley & Sons Ltd.

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KEY WORDS: laser; peel-seal; bond; scanning; non-contact

INTRODUCTION

Localized bonding between polymer laminates has risen to become a pivotal technology[1] that, in 2005, powered a worldwide £420bn industry that consumes between 30 and 35% of all polymers.[2,3] The modern consumer lifestyle relies upon this industry to underpin packaged products and robust logistics. Preservation of packaged food stuffs requires consistent bonds between laminates.[4] Because of this, valuable intellectual property has developed concerning the conditions needed to create various types of seal.[1]

The most conventional approach to thermal bonding of polymers employed by the food industry involves a thermally activated polymer adhesive coated film applied to a substrate during adhesion, as

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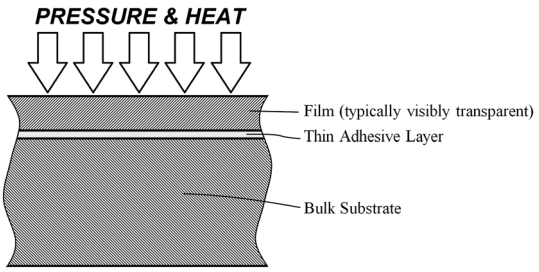

Figure 1. Schematic showing typical arrangement of polymer layers in contact bonding.

shown schematically in Figure 1. This is a contact process where conduction is relied upon to transfer energy from a continuously heated contoured steel element that is forced onto the film to ensure contact with the bulk substrate, heat and trim the film. Bond strengths in the region of 0.5 N/mm are quoted when the element is above the threshold bonding temperature of the polymer adhesive film.[5] This method suffers from process inflexibility and mechanical wear that leads to service downtime[6]; meanwhile, reliance upon thermal conduction and diffusion leads to limited processing speed[7] and high energy consumption.[8] Nevertheless, the perceived simplicity of a contact-based system has led to universal adoption of the contact-based method.

Contact between material layers, the application of heat and the duration of contact between the heating element and the film (dwell time) are the primary parameters in contact-based adhesive polymer film bonding.[9] Dwell time must be sufficient to supply a thermal load to activate the adhesive[9]; bond strength is related to element temperature.[10] It is likely that high contact pressure merely ensures uniform contact across large area, non-flat (because of machining tolerances) heating elements.[9] A laser-delivered thermal load can replicate these conditions with the added benefits of a non-contact methodology.[11] Continuous wave infrared marking lasers have been used successfully for highly consistent non-contact selective thermal bonding of polymer laminates.[12]

Brown et al.[13] successfully demonstrated the laser welding of a non-specified, application bespoke thermoplastic multilayer film applied to container substrates for aseptic food packaging using a 50 kW CO_2 laser source with a beam quality characteristic (M^2) of less than 1.2. The experimental set-up incorporated a film stretched over a rectangular frame, with two reels for ensuring tension and a scanning galvanometer for manipulation of the beam.

The effect of foreign body contaminants along the weld seam was studied, and it was found that the cause of weld defects in the presence of contaminants was because of a lack of contact between the film and substrate. The ingress of oxygen after sealing of containers was also investigated, with approximately 70% of samples produced failing an oxygen transmission test. However, the weld integrity regarding egress of liquids proved to be more successful. Containers were filled with water and isopropyl alcohol and stored upside down of a period of 2 years with no seal failure encountered.

In a follow-up publication,[14] Brown et al. investigated the CO_2 laser welding of 105 μm thick PP-based multilayer polymer film to a polyethylene terephthalate (PET) container tray. In the earlier paper, scanning speeds of approximately 200 mm/s were found to produce the best quality seals. However, it is noted that these speeds are too slow for industrial applications. As such, the sealing process was optimized for higher scanning speeds of $\leq$4.7 m/s. The authors were unable to determine the upper limit of processing speed as a result of the limited power of the laser but demonstrated that through compensating by increasing power and decreasing spot size, the processing speed of laser welding of polymers can be increased. A further follow-up publication[15] investigated the CO_2 laser welding of commercially available 26 μm thick Esterpeel film with an amorphous PET sealing layer to a PET container tray. The study focussed once again on improving throughput to match conventional sealing processes, quoted here as producing up to 60 seals per minute. However, the prototype laser-based system was only capable of 12–15 seals per minute and was subject to repeatability issue regarding the integrity and strength of the seal.

A state of the art 3 kW contact-based system requires 20.7 kJ per tray[16] once the system has been heated (requiring energy and time investment). Previous work[12] has demonstrated that a 25 W CO_2 laser (requiring a maximum of 2.5 kW electrical input) can immediately develop a strong bond at 54.4 mm/s, thus using approximately 15 kJ for an equivalent tray. This indicates a significant financial

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operating cost saving for the laser technique as well as the associated environmental CO_2 output reduction benefits. There are many other exemplary processes where lasers are competitively employed for accurate, adaptive and selective bonding and welding applications for a variety of materials.[17–19] The key benefit of laser beam processing lies in its adaptive nature; laser energy can be delivered via galvanometric mirrors to a desired location on-demand (without lengthy warm-up times) at a desired traverse velocity, thus affording the user great geometric flexibility, high spatial control as well as continuous tray motion.[20] In contrast, the competing contact-based method must have pre-defined geometry, requires lengthy warm-up and cool-down periods when re-tooling, are mechanically complex and prohibitively expensive to purchase.[16,21]

Accurate characterization of the laser-motivated thermal activation of polymer adhesives is critical to the implementation of non-contact polymer bonding. Previous work[12,22] has demonstrated bond consistency, peel resistance comparable to that achieved by contact-based methods, a relationship between laser irradiance and peel bond strength within a narrow range of irradiance and indicated a consistent adhesive regime bond for larger irradiance values. However, this is not sufficient to characterize the material response to laser exposure, thus leading to the subject of this work. In this paper, the laser heat sealing of a commercial visibly transparent linear low density polyethylene (LLDPE) lid-stock film (Cryovac, Sealed Air Corporation.) that was pre-coated with a proprietary thermally activated adhesive to a polypropylene (PP) bulk substrate using a specially designed experimental arrangement incorporating a scanning CO_2 laser system is conducted. The effect of power, line energy and irradiance on the ability to generate a meaningful bond is investigated.

EXPERIMENTAL METHODOLOGY AND PROCEDURE

The arrangement of material handling equipment

The critical requirement of any polymer thermal bonding system is reliable and consistent contact between the film and base polymer to ensure a functional bond.[7] This is inherently provided by the contact methodology of traditional sealing systems: These force the substrate onto the film, allowing thermal conduction and, in some cases, an opportunity to trim unnecessary material from the edge of the item being sealed.[5]

This requirement remains for any non-contact bonding methodology to allow functional activation of the adhesive. A system has therefore been developed for this series of experiments to provide reliable contact between the film, adhesive and substrate following the schematic arrangement of Figure 2. This arrangement rigidly supports a CW marker laser (Fenix Flyer; Synrad, Inc.) that has been modified to use a non-standard Ø48 mm single element wide area scanning lens, held in place with a specially made collar to hold the lens in a suitable position for the galvanometer arrangement of the laser. A working distance of 450 mm was required, provided by a variable lift stage in the support frame. The 75 μm thick LLDPE lid-stock film was supplied from a 600 mm wide clutched reel having been pre-coated with a thin layer of thermally activated adhesive by the supplier and drawn taught by clutched reels; film tension can be varied by adjustment of reel clutches. The thin nature of the adhesive layer differentiates this technique from 'clear welding'.[16] The film passes under two crowned

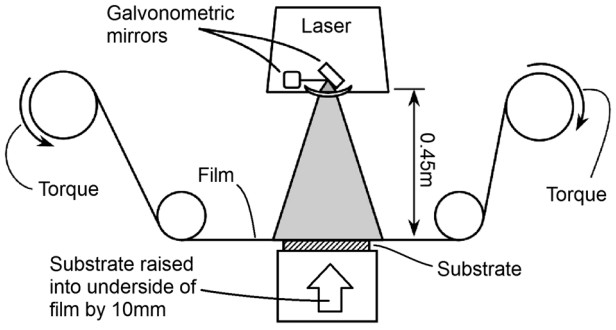

Figure 2. Schematic arrangement of material handling during laser irradiation.

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rollers to ensure prevention of wrinkles developing as the film was drawn through the system. The substrate material, 640 μm thick PP sheet, was pushed up into the film to a plane that coincides with the laser beam spot size desired.

Laser control

Laser control was provided by the supplied software (Winmark Pro Version 6.2.0; Synrad, Inc), using the 200 mm working distance lens setting in conjunction with the replacement lens to achieve a wide, 335 × 335 mm, machining area without spherical distortion. Four incident laser beam spot diameters were used: 0.0006, 0.0010, 0.00140 and 0.0020 m; for every one of these spot diameters, seven traverse velocities were applied: 0.0405, 0.0473, 0.0540, 0.0675, 0.0743 and 0.0810 m/s (after lens scaling correction) were used. To achieve bonds over the varying spot sizes, differing laser powers were required for each spot size; these are detailed in Table 1. Figure 3 details a single sample; these appear as six tracks (which have the appearance of stitch patterns), each track is machined using a single approach. Multiple tracks are machined for reduction in random error. Every sample was machined at one of the pre-determined velocities stated in the preceding texts. Every track is bounded by a gate stitch; these are machined for three purposes: (a) to instigate lasing before bond stitches (for laser consistency), (b) to protect the bond stitches from post processing damage in transit and (c) to initiate data sampling during peel testing. Every bond stitch in a track represents an increase in laser power as reported in Table 1; often multiple samples are required to cover the range of powers tested.

Table 1. Tabulated line energy, measured laser power and the requested output of the laser.

	Spot diameter (m)			
	0.0006	0.0010	0.0014	0.0002
MEASURED LASER POWER (W)	22.8	23.3	23.8	26.9
	21.8	22.3	22.8	26.1
	20.8	21.3	21.8	25.6
	19.7	20.3	20.8	25.2
	18.6	19.2	19.7	24.7
	17.5	18.1	18.6	24.3
	16.4	17.0	17.5	23.8
	15.2	15.8	16.4	23.3
	14.0	14.6	15.2	22.8
	13.3	13.3	14.0	22.3
	12.7	12.1	13.3	21.8
	12.2	11.4	12.7	21.3
	11.4	10.8	12.1	20.8
	10.8	10.1	11.4	20.3
	10.1	9.44	10.8	19.7
	9.4	8.76	10.1	19.2
	8.76	8.07	9.44	18.6
	8.07	7.38	8.76	18.1
	7.38	6.68	8.07	17.5
	6.68	5.97	7.38	17.0
	5.97	5.25	5.25	16.4
	5.25	4.52	4.52	15.8
	4.52	3.79	3.79	15.2
	3.79	3.05	3.05	14.6
				14.0
				13.3
				12.7
				12.1
				11.4
				10.8
				10.1
				9.44
				8.76

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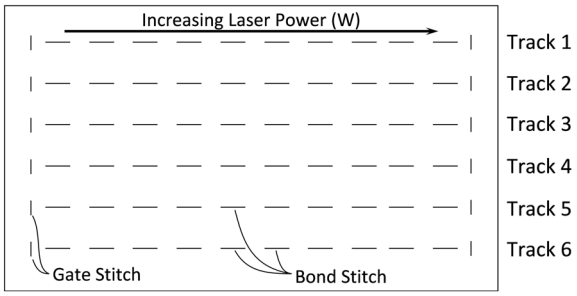

Figure 3. Schematic arrangement of a laser-machined sample.

Beam analysis

The beam generated had an experimentally determined M^2 value of 5, with a profile as characterized in Figure 4. Machining was conducted significantly out of focus to achieve the pre-determined incident laser spot sizes quoted in section 2.2. The laser beam power was verified using a laser power meter (UP25N250FH12, Gentec Electro-Optics, Inc.) attached to a calibrated meter (Maestro, Gentec Electro-Optics, Inc.). Actual beam power was measured with respect to requested percentage of maximum laser duty cycle, yielding an average power with respect to duty cycle relationship. Repetition of this process demonstrated that laser power varied by less than 2%. A function relating absolute incident laser beam power to the laser's duty cycle has been calculated using the least squares method in a commercial spreadsheet software (Excel 2010, Microsoft Corp.).

Peel force measurement

Each laser-bonded track was separated using a guillotine (Staples, Ltd.) to minimize shear applied between film and substrate during cutting. A sample then consisted of six separate objects that were each peeled individually. The use of six tracks allows for track damage and systematic error reduction by the use of mean averaging of the peel force data.

Each track's PP substrate was bonded to a translating trolley stage, and the LLDPE film was clasped as shown schematically in Figure 5. This arrangement adheres to a commonly applied industrial standard (ASTM: B571). The film was peeled perpendicular to the bond direction (thus, avoiding trigonometric amplification of the recorded peel resistance force) using a calibrated tensile tester (3340 Single Column Testing System, Instron Corp.) with a bespoke translation peel testing accessory (Constant 90° Angle Peel Fixture, Instron Corp.). This peel arrangement was applied to better simulate the scenario of a film peel from a rigid tray substrate (as experienced by an end user). Every sample was

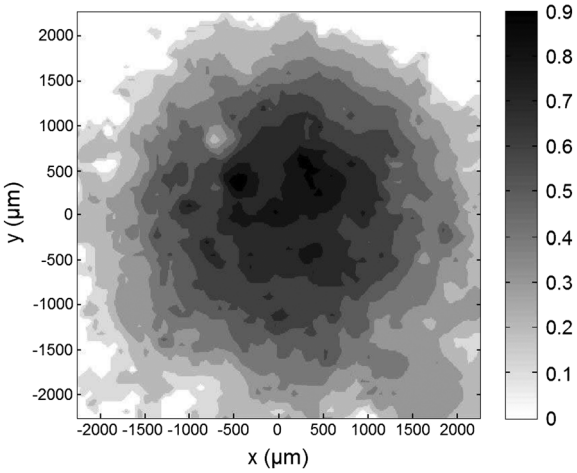

Figure 4. Spatial plot of beam shape.

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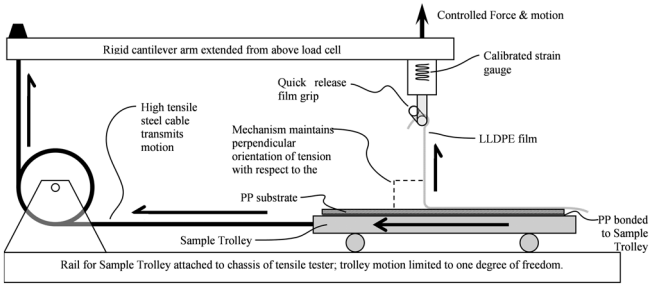

Figure 5. Schematic diagram of material handling for peel testing.

peeled using this arrangement at a rate of 5 mm/s. A key feature of this arrangement was the ability to maintain the orthogonality of tension force with respect to the plane of the substrate. The quick release clasp used (Thin Film Grips, Instron Corp.) ensured that minimal force was exerted to the sample prior to testing. The gate bonds shown schematically in Figure 3 also protected the bonded sample stitches from peel force prior to analysis. This equipment greatly improved upon the arrangement previously used[12,22] in terms of statistical exclusivity and methodological repeatability. The stitch arrangement provided sufficient peel duration to allow the resistance force to stabilize, as defined by Brown et al.[13] providing a repeatable and reliable measurement, as borne out by the standard deviation values reported in the results of this work.

The peel force was sampled at 100 Hz, and peak peel resistance force values were yielded by RMS algorithm filters in a PC-based analysis software (Bluehill 2, Instron Corp.) before being exported as a comma delimited script for compilation using a commercial spreadsheet software (Excel 2010, Microsoft Corp.).

Assumptions for statistical peel classification

The terminology used to describe the regime of join between laminates is critical to this work; as such, 'bond' refers to any general join achieved, 'adhesion' refers to any join achieved by the activation of an adhesive, and 'weld' describes any join achieved by the melting, coagulation and solidification of the polymers involved.

Several experiments were conducted in this work, as presented in the sections in the preceding texts; all concerned laser processing and peel strength measurements. In order to identify both 'good results' (optimum seals) as well as 'good process parameter values' (viable seals), values of references must be chosen. To do this, a threshold value, under which a viable seal was not achievable, was arbitrarily defined by the authors:

A threshold value of 1/5th the maximum registered mean peel resistance force deemed to represent the initiation of a meaningful bond was identified for each spot size. Values that fall within a ±10% (of the maximum registered peel resistance force) range of this threshold value represent the lower limit under which a seal was acceptable.

RESULTS AND DISCUSSION

Mean peel resistance force performance with respect to laser spot size

The raw data can be observed in the context of peel resistance force performance with respect to spot size in Figure 6. In all of these contour plots, the mean peel resistance force (each value having been derived from six separate bond samples) is stated with respect to both laser spot traverse velocity and measured laser power; it is important to note that both these parameters are involved in the definition of the irradiance parameter, which is the key parameter for the characterization of the process because it involves all parameters modulated in this work. Irradiance is defined by the following formula:

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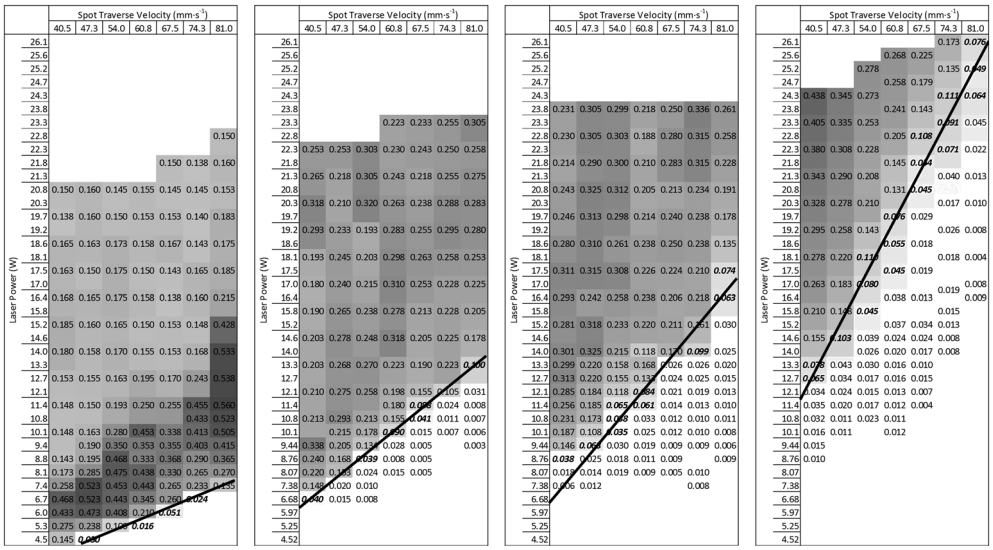

Figure 6. Graduated map of peel resistance force with respect to spot traverse velocity and laser power for (a) 0.6; (b) 1.0; (c) 1.4 and (d) 2.0 mm incident laser spot diameters, respectively. Light shading indicates low peel resistance; dark shading indicates high peel resistance.

$$I = \frac{2P}{\pi v_0 \omega_0} \tag{1}$$

which is dimensionally analogous to intensity and factors in an effective dwell time (d_0/v_0) where ω_0 represents the spot radius, v_0 is the laser traverse velocity and P is the incident laser power.

For all contours plotted in Figure 6, the lowest peel resistance force is represented using pale cell shading, whereas maximum peel resistance force is identified using dark cell shading. Viable peel resistance force values (1/5th maximum registered peel resistance force as described in Section 2.5) are indicated as bold italicized values.

The following paragraphs describe, in detail, each contour included in Figure 6; in particular, three main characteristics were compared: (a) incident laser spot traverse velocity; (b) incident laser power and (c) peel resistance force.

Figure 6a represents a 0.6 mm laser spot diameter.

1. A sharp gradient of *peel resistance performance* increase with respect to irradiance.
2. **A** *peak peel resistance performance* with respect to irradiance that is maintained across a narrow region of the contour plot.
3. The shallowest trend in *bond initiation* with respect to irradiance of all the plots given in Figure 6.

One aspect of Figure 6a that is not apparent for any of the other contours plotted in Figure 6 is the recession in peel resistance force above a threshold laser irradiance of approximately 270 kJ/m^2; this is represented by a combination of both the transverse velocity and power values that are located at the upper left quadrant of Figure 6a. Previous work[11] that used LLDPE and PP suggested that excessive laser irradiance can result in polymer welding, which although strong, is erratic. This work, however, trialled the bond achieved when using the LLDPE film in both orientations. The LLDPE did not bond readily with PP when the adhesive-treated side of the LLDPE was not in contact with the PP (as reported by others[23]), confirming that the process observed throughout this paper was the result of an adhesive bond, not a welding phenomenon; a *hypothesis* supported by the differing material properties of the two laminates concerned.[24]

Figures 6b, 7c and 7d represent 1.0, 1.4 and 2.0 mm diameter laser spot sizes, respectively; all exhibited similar trends:

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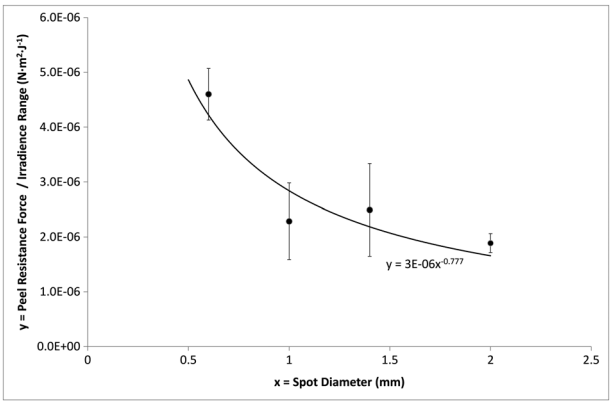

Figure 7. Relationship between the gradient of peel resistance force increase with respect to laser irradiance increase and incident laser beam spot size. Error bars represent the standard deviation of the data analysed.

1. A shallower gradient of peel resistance force with respect to irradiance than that of the 0.6 mm spot in Figure 6a.

This gradient reduces consistently with respect to spot size throughout all data collected.

2. The peak peel resistance performance with respect to irradiance is maintained across a broader region of the contour plot (if compared with Figure 6a).

This trend grows with respect to spot size throughout all data collected.

3. The *viable bond irradiance* gradient increases with respect to spot size throughout Figure 6.

An overall trend can be seen in Figure 6 that indicates that the range of useful laser irradiances is proportional to incident laser spot size; this is because the contour gradient running diagonally up and to the left of every contour reduces with increasing spot size, suggesting increased range of operation.

Abruptness of transition

All of the data presented and analysed thus far has described the laser exposure threshold for viable use of the laser for bonding; this discussion has been made irrespective of the ease of achieving such laser parameters. This facet of laser operation can be defined as the operational processing window, i.e. the range of laser output where a bond can be produced that lies between viable and acceptable (any peel resistance force larger than viable). In this contribution, this has been achieved by measuring the mean gradient of the peel resistance force achieved over the viable laser irradiance range (between viable and optimum bonds) with respect to incident laser spot diameter. The results of this analysis are plotted in Figure 7. A lower force/irradiance range represents a wider processing window because it means that a larger proportion of the laser's output can be applied to produce a viable bond, thus allowing the user to home in upon the optimal laser parameters more easily. A broad processing window also leads to operational stability because small variations in the temporal laser intensity will make little difference to the peel resistance force achieved in the bond.

Figure 7 shows that the 2.00 mm spot diameter data has a gradient that appears to be an outlier; this is understandable given the low probability of the true peak peel resistance force being represented in the data collected. This apparent lack of conformity for the 2.00 mm spot diameter in Figure 7 is likely to be the result of the algorithm used to calculate the mean peel resistance force/irradiance gradient that would be greatly affected by the power and traverse velocity sampling resolution. This is especially true for the 2.0 mm diameter spot size given that the data collected for these samples occurred at the top of the laser's duty cycle; inspection of Figure 6d would tend to support this explanation.

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Incident laser-material interaction required to initiate adhesive bonding

The peel resistance force of a viable bond is specified in the section 2.5; hence, the results plotted in Figure 8 represent the 20th percentile of the maximum peel resistance performance achieved with respect to traverse velocity for each of the four laser spot sizes trialled. Where more than one peel resistance force signal fell within the stipulated 20% range (described in the preceding texts) per traverse velocity trialled, the mean of all of the qualifying data is taken; as such, standard deviation bars are also provided in Figure 8 for these points to indicate the accuracy of this averaging technique.

The data plotted in Figure 9 verifies the qualitative observations made using Figure 8: The data points universally follow a clear linear trend for every laser spot size trialled; furthermore, the gradients of these trends increase proportionally with respect to laser spot size. This demonstrates that accurate process control can be achieved by the modulation of laser power, laser spot traverse velocity or incident laser spot diameter.

This hypothesis is supported by the data plotted in Figure 10. This data demonstrates that a specific area of material requires a threshold level of laser beam exposure (irradiance) to achieve a viable bond. Irradiance, which is measured as J/m^2 (dimensionally identical to laser beam intensity, I), differs from beam intensity in the reference frame used: Irradiance describes the laser energy witnessed at the material surface with respect to irradiated area whilst intensity is the mean energy density within the incident beam. As such, irradiance is the product of laser power, incident spot size and spot traverse velocity, whereas intensity only involves laser power and incident spot size.

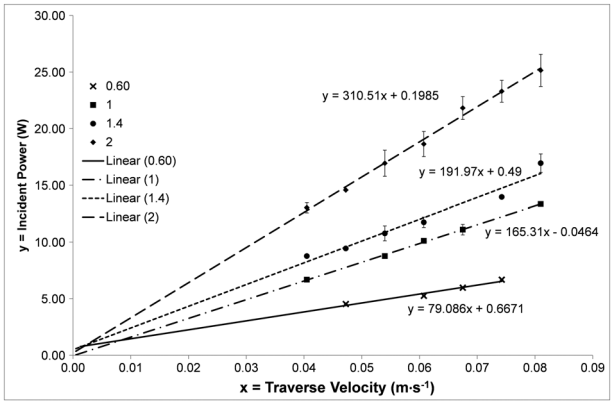

Figure 8. Incident power required to initiate adhesive bonding with respect to traverse velocity for laser spot diameters of 0.6, 1.0, 1.4 and 2.0 mm.

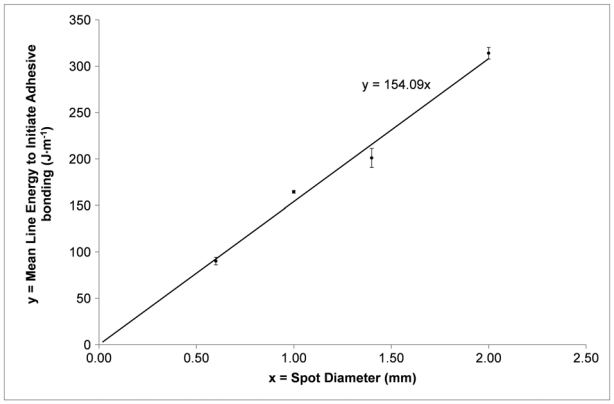

Figure 9. Mean line energy required to initiate adhesive bonding with respect to spot diameter.

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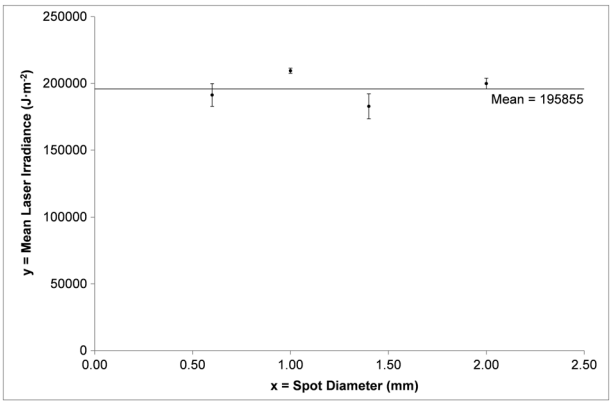

Figure 10. Mean irradiance required to initiate adhesive bonding with respect to spot diameter.

Figure 10 characterizes the delivered energy density requirement for peel-seal viability. Figure 10 is plotted using Equation 1. Figure 10 demonstrates that the irradiance required to achieve a viable bond (20% of the max bond strength achieved) is constant with respect to varying spot size. As discussed in the preceding texts, this is to be expected if the materials bonded exhibit linear thermal expansion rate properties (as confirmed in Figure 9) because the results analysed are normalized against peel resistance force (to produce results calibrated against potential performance, rather than absolute performance).

Irradiance-based predictions of laser sealing

The mean irradiance required to achieve a viable seal (indicated in Figure 10) enabled the development of a relationship to predict incident laser power required for a given laser spot size and scanning traverse velocity to achieve a viable bond. The irradiance, as described in Equation 1, can be used to relate incident laser power to the spot diameter, and laser traverse velocity is described by the term

$$P = \frac{\pi v_0 \omega_0 I}{2} \tag{2}$$

The relation given in Equation 2 is plotted as a laser power contour in Figure 11 that allows the easy reference of laser power required to achieve a viable bond given a known requirement of laser spot diameter and scan traverse velocity for this laser wavelength and material combination used in this work.

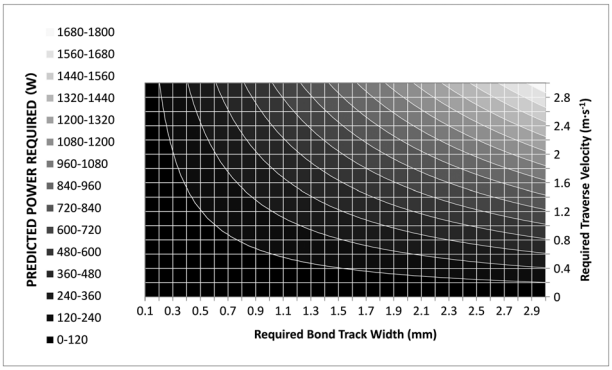

Figure 11. A surface plot indicating the laser power required to achieve a viable bond given a known required scan traverse velocity and desired bond width; values are calculated from the empirical relation defined from the empirical relation defined from Figure 10.

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CONCLUSIONS

The mean peel resistance force of commercial LLDPE 75 μm thick lid-stock film backed by a commercial adhesive coating that were bonded to a substrate of 640 μm thick PP sheet via thermal activation provided by a 10.6 μm wavelength 27W CO_2 scanning head delivered laser were measured using a 90° peel arrangement conforming to ASTM: B571. The force data generated is analysed in this contribution with respect to variation in the laser power, incident spot traverse velocity and incident spot diameter to achieve a parametric sweep. The results can be summarized as the following:

1. Viable adhesive bonds (measured around the 20th percentile of the maximum peel force recorded at each laser spot diameter) were demonstrated to be achievable, reliably produced and exhibited a dependency upon laser parameters.
2. The abruptness of change between no seal and viable seal was shown to vary with respect to spot size (i.e. the size of the operational processing window can be increased by increasing the spot diameter).
3. A novel tool has been developed that will enable users the ability to select a laser given that other operational parameters are known.

All results used in this analysis used a sampling range of ±10% around the performance level of interest, from which a mean laser parameter value was taken.

The results of this work demonstrate that a linear increase in laser line energy of 154 J/m was necessary per millimetre increase in laser spot diameter for the LLDPE on PP combination used. Furthermore, the results indicated a high level of repeatability around this threshold laser line energy value suggesting that the laser activated adhesive bonding technique described in this work is viable. These conclusions for viable bonds are supported by analysis of the laser irradiance required for adhesive activation that demonstrated a relatively close consensus around a mean value of 196 kJ/m for every spot size trialled. This is the irradiance response behaviour of a material combination that responds linearly to thermal load because the energy density required to be delivered to the material for adhesive remains constant.

The results described have been used to generate an empirical CO_2 laser power prediction chart for achieving a viable bond using a LLDPE on PP combination. This novel contribution is a critical technique to be applied in an industrial setting with accuracy, ease and low cost.

The maximum peel resistance force delivered by the 0.6 mm diameter spot size (the smallest tested) was significantly greater than any achieved using the larger spot diameters tested; furthermore, the peak peel performance recorded for 1.0, 1.4 and 2.00 mm all sit along a linear trend, which is not adhered to by the 0.6 mm result. It is proposed that the high irradiance possible using the 0.6 mm diameter laser spot caused a more substantial bond than that achieved using larger spots without the erratic nature reported for LLDPE on PP in previous work.

The comparison between the mean gradient of the peel resistance force range with respect to the range of laser irradiance used to produce them has been mapped to the four incident laser spot diameters applied to the LLDPE on PP material combination. This has demonstrated that the processing window of an incident CO_2 infrared laser spot increases with respect to incident spot diameter. A low gradient indicated gradually increasing peel resistance force; thus, it is indicated by this work that larger spot diameters offer broader operational processing windows and greater stability in the face of short-term laser instability.

REFERENCES

1. Hishinuma K. *Heat Sealing Technology and Engineering for Packaging: Principles and Applications*, DEStech Publications: Lancaster, PA. 2009.
2. Duffy E, Hearty AP, Flynn A, McCarthy S, Gibney MJ. Patterns of intakes of packaged foods in Irish children aged 5–12 years, *Food Additives & Contaminants* 2006; **23**: 715–725.
3. Hopewell J, Dvorak R, Kosior E. Plastics recycling: challenges and opportunities. *Philosophical Transactions of the Royal Society B* 2009; **364**: 2115–2126.
4. Harper CL, Blakistone BA Litchfield JB, Morris SA. Developments in food packaging integrity testing. *Food Science & Technology* 1995; **6**(10): 336–340.

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5. Promotional Material. Reliable and versatile performance for easy-open packaging, The Dow Chemical Company, Inc. 2010.
6. Coles R, McDowell D, Kirwan MJ. *Food Packaging Technology*; Blackwell. Oxford: UK, 2003.
7. Troughton MJ. *Handbook of Plastics Joining: A Practical Guide*, 2nd edn.. William Andrew: Norwich, NY 1998.
8. Promotional Material. FS910 Thermoforming Machine, Mecapack SA. Italy 2012.
9. Yuan CS, Hassan A, Ghazali MIH, Fauzi Ismail A. Heat sealability of laminated films with PAO and LDPE as the sealant materials in bar sealing application, *Journal of Applied Polymer Science* 2007; **104**: 3736–3745.
10. Mueller C, Capaccio G, Hiltner A, Baer E. Heat sealing of PAO: relationships to melting and interdiffusion. *Journal of Applied Polymer Science* 1998; **70**: 2021–2030.
11. Steen WM. *Laser Material Processing*, 3rd edn., Springer: London, 2003.
12. Dowding CF, Lawrence J. Characterization of the peel resistance force achieved and threshold line-energy required when laser bonding linear low density polyethylene film to polypropylene using a commercial adhesive. In *Proceedings of the 37th International MATADOR Conference*, Hinduja S, Li L (eds). Springer: London, 2013; 445–448.
13. Brown N, Kerr D, Jackson MR, Parkin RM. Laser welding of thin polymer films to container substrates for aseptic packaging. *Optics & Laser Technology* 2000; **32**: 139–146.
14. Brown N, Shi F, Kerr D, Jackson MR, Parkin RM. CO_2 laser processing of multilayer packaging films. *Proceedings of the IMechE Part I:J Systems Control and Engineering* 2005; **219**: 231–237.
15. Brown N, Kerr D, Parkin RM, Jackson MR, Shi F. Non-contact laser sealing of thin polyester food packaging films. *Optics and Lasers in Engineering*2012; **50**(10): 1466–1473.
16. Promotional Material: S1500 Automatic Sealing Machine, Mecapack SA, Italy (2012).
17. Woosman NM. Clearweld: welding of clear, coloured, or opaque thermoplastics. *Proceedings of the Institution of Mechanical Engineers D-Journal Automobile* 2005; **219**.
18. Hilton PA, Jones IA, Kennish Y. In *First International Symposium on High-Power Laser Macroprocessing*, Miyamoto I, Kobayashi KF, Sugioka K, Poprawe R, Helvajian H (eds). SPIE: Osaka, Japan: 2003, 44–52.
19. Sun Z, Ion JC. Laser welding of dissimilar metal combinations. *Journal of Materials Science* 1995; **30**.
20. Ion JC. Laser processing of engineering materials: principles, procedure and industrial application; Butterworth-Heinemann, UK 2005.
21. Promotional material: S2000 Automatic Sealing Machine, Mecapack SA, Italy 2012.
22. Dowding CF, Dowding RG, Griffiths J, Lawrence J. Peel resistance characterization of localized polymer film bonding via thin film adhesive thermally activated by scanned CO2 laser. *Optics and Laser Technology* 2013; **48**: 358–365.
23. Klien R. *Laser Welding of Plastics*, Wiley-VCH Verlag GmbH & Co. KGaA: Germany, 2011.
24. Birley AW, Batchelor J, Haworth B. *Physics of Plastics*. Hanser Gardner Publications: Munich, 1997.

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