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An empirical investigation into the influence of sealing crimp geometry and process settings on the seal integrity of traditional and biopolymer packaging materials

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Abstract

This paper presents the results of investigations to determine how process settings and crimp geometry affect the seal strength and integrity of traditional polyolefin and biopolymer flexible packaging materials. The results show that, as with previous temperature and dwell time are the dominant factors for both polyolefin and biopolymer films. Pressure and crimp geometry are shown to be secondary factors in the process, up to the point of squeezing the film into molecular contact. In general it is shown that biopolymers exhibit similar sealing characteristics to the traditionally employed films. In respect of the sealing crimp geometry it is shown that the crimp pitch has little or no effect on sealing integrity for films with gauges between 25µm and 40µm. But, for the same gauge material, crimp angles greater than 80° offer the greatest potential to gain higher seal strengths. It is further shown that with the cellulose and PLA films tested, a higher seal strength can be produced with crimp pitches of 2mm and lower. Also presented are some more general implications for determining the geometry of sealing crimp designs and their usage along with biopolymers.

INTRODUCTION

Although the UK has met its 2010 Landfill Directive[1] targets to reduce the amount of biodegradable refuse sent to landfill, the volume of plastics entering the waste system is still rising. There are approximately one million tons of domestic mixed plastics packaging waste disposed of in the UK each year and of this 75% is made up of polyolefins[1] (the conventional oil-based polymers). The flexible polymers used in bags, pouches and over-wrapped products make up 30% of all plastic packaging waste. There are two areas in which the food industry is attempting to reduce the volume of oil-based polymers entering the waste system. The first seeks to gain improvements for in-process effectiveness, reducing the volume of seal failures in production. The second is increasing the adoption of biopolymer films which are made from sustainable sources with compostable properties.

Within the food industry, constant heat bar sealing is the most widely employed method to produce a seal in form-fill-seal operations [3]. It is commonly accepted that there are three dominant parameters in this process: sealing temperature, dwell time, and sealing pressure. It is also acknowledged that to obtain an integral seal, these three parameters need to be set in a proper combination during the heat-seal cycle and related to the material to be sealed [3-8]. While these variables are proven to affect the resultant seal integrity, it is the design of the sealing crimp that forms the main point of interaction between the polymers and machine. Therefore in achieving the aim of reduced oil-based polymer waste entering the waste system, an increased understanding of the sealing zone and especially the optimal design of the sealing crimp becomes vital.

The focus of the work reported in this paper is seals produced using form-fill-seal operations[3]. With such systems, material is fed from a roll and converted from its planar (web) form via a forming box/shoulder into a tubular form with a small overlap which is sealed. Once the material has been pulled past the box/shoulder, sealing crimps come together and seal across the web. This means that the material now presents a “pocket” into which product can be inserted. The material is then advanced and the sealing crimps come together again to close the bag/pouch. If required, a blade within the crimps separates the bag/pouch from the rest of the tube [9].

Constant heated sealing (CHS) is the most popular technique for producing seals [3,7]. With this technique, a solid crimp bar is heated to the required temperature and kept constant. Figure 1a show such crimps on a vertical form-fill-seal machine. It is common that the front faces of such crimps have profiles machined into their surface. In the example shown in Figure 1a, a triangular geometry, similar to that shown in Figure 1b has been machined horizontally along the length of the crimp. In general the crimp geometry is constructed from four specific variables (cf. Figure 1b): the pitch (*p*), the crimp angle (*α*), and the top and bottom crimp radii, *r1* and *r2* respectively.

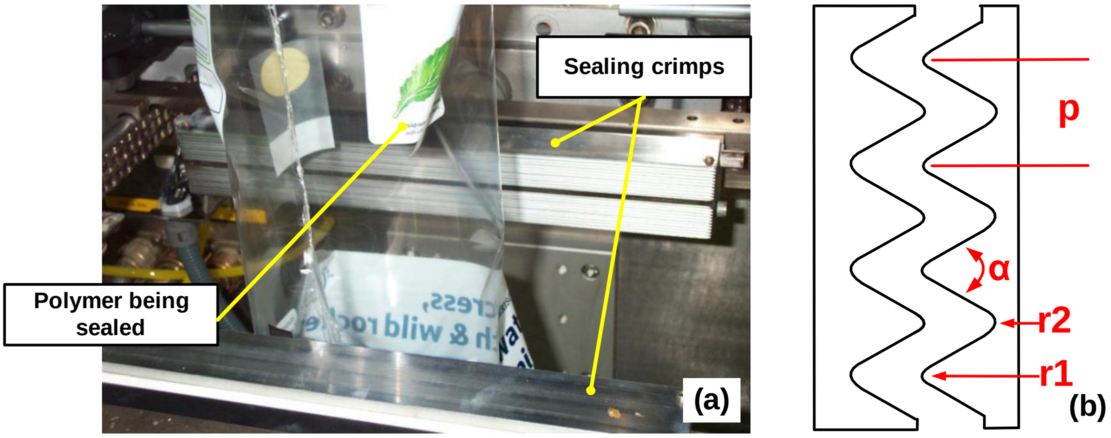


Figure 1 Sealing crimps and crimp parameters

BACKGROUND

Much of the previous literature relating to polymers and heat sealing has focused of the heat-seal cycle parameters and their effects on seal strength. The first major study on the heat sealing process was performed by Theller[4]. This reported that the interfacial temperature and dwell time are the primary factors in controlling heat-seal strength. Pressure normal to the seal surface had little effect above the level required to flatten the web for good contact. Meka and Stehling [5,8] investigated the effects of heat-seal cycle parameters on the seal properties (seal strength, seal elongation, and seal energy) of polyethylene films. In these studies it was shown that to obtain the highest possible seal strength for a given semi-crystalline polymer, the required heat bar temperature can be estimated for the given dwell time and interfacial temperature by a finite element model. Their results agree with Theller and other works [6,7] where heat seal strength is primarily controlled by sealing temperature and dwell time, rather than pressure. They also established the relation between the seal strength and heat bar temperature. From this, significant heat-seal cycle quantities such as seal initiation temperature, plateau initiation temperature, final plateau temperature, and plateau seal strength are identified for crystalline polymers.

The core function of the sealing crimp is to “squeeze” the two layers of film to achieve as high molecular contact over as much of the sealing area as possible within the constraints of the bag/pouch design. Some limited work on the design of the sealing system has also been undertaken. Aithani *et al.* investigated the impulse heat sealing process for a variety of materials [6], while de Oliveria *et al* [10] evaluated the influence of the sealing crimp profile on the quality of heat seals with two materials: bi-axially oriented metalised polypropylene/low density polyethylene and bi-axially oriented metalised polypropylene/bi-axially oriented polypropylene. The heat sealing temperature and dwell time were optimized for these materials and the sealing pressure was fixed at a value of 40 lbf/in^2 (2.75 bar). Heat sealing quality was evaluated through visual examination, integrity, tensile strength and drop testing. The tests attempted to replicate the transportation of the product after packaging. Their results showed that in simulation, the product transport process reduced the resultant heat sealing quality for all profiles of crimp tested.

In previous research, the emphasis has been on the usage of conventional oil-based polymers (polyolefins). With the dwindling supplies of oil, academia and industry are currently developing biopolymers, which are materials derived from renewable and sustainable sources[11]. These can be broadly divided into three main categories based on their origin and production[12]:

- C1 polymers directly extracted/removed from biomass e.g. polysaccharides such as starch and cellulose;
- C2 polymers produced by classical chemical synthesis using renewable bio-based monomers e.g. polylactic acid (PLA) which is a biopolyester polymerized from lactic acid monomers; and
- C3 polymers produced by microorganisms or genetically modified bacteria e.g. polyhydroxyalkonoates.

Currently it is only the films from categories C1 and C2 that are commercially available in volume for packaging operations. Previously biopolymers have not lent themselves to food applications with high moisture content or requirements for long shelf-lives[12]. This is because such films have a tendency to show degradation of mechanical properties over time, which conventional oil-based polymers do not suffer from. However recent developments in polymers construction and laminations of biopolymers to conventional polymers are reversing this. Furthermore reporting of investigations into the sealing characteristic of such biofilms has been limited to that of Farris *et al.*[13] who showed that such layers offer comparable seal strength to the existing polyolefins which industry currently used, and the works of Su *et al*[14] who investigated the heat-sealing properties of blends of soy protein isolate and polyvinyl alcohol blends which they developed.

So, while much of the existing research has set the foundations for sealing understanding, there still exists some gaps. From an industrial perspective, seal initiation temperature (the point where the film starts to bond) is a very important property of film packaging. A lower seal initiation temperature is desirable and results in lower energy costs, a broader heat-seal range (sealing envelope), and higher production rates[15]. As the seal crimp is the main interaction with the film, it is also important that the geometry aids the process of heat energy flow. Potentially poor crimp geometry can result in increased energy costs and a smaller sealing envelope. Most of the previous research noted has used flat crimp profiles in their evaluations of the heat-seal cycle [6-8, 12]. In particular, such profiles have been shown to be unreliable and produce a weaker seal than serrated crimps. For this reason they are not employed in industrial form-fill-seal applications. Beyond this, research into crimp geometry has been limited to the works of de Oliveria *et al* [10]. Much of the reviewed work uses lengthy dwell times (more than one second), which are unrealistic in modern packaging companies, where dwell times of 0.3-0.5 seconds are required [16]. Beyond reviews of applications[11,12], little work has been reported on biopolymer films and the effect of the crimp profile on their seal integrity. It is the intention of this study to address these gaps, and present finding that can help fast moving consumer goods companies to increase process effectiveness for both polyolefins and biopolymers, and hence potentially reduce polymer waste entering landfill.

EXPERIMENTAL APPROACH

The study undertaken here examines seals produced in bags under a variety of operational conditions. The seals were produced using a Hayssen-Sandiacre 2540 vertical form-fill-seal machine using a supplied crimp set. This used a pitch of 0.085" (2.15mm) and a crimp angle of 90°. The crimp closure time was validated using a Fastec troubleshooter™ high speed camera. The crimp temperature was set and measured by the machine's thermocouple and controller, but the surface temperature was determined using a Precision Plus PT100 high accuracy thermometer. The crimp pressure was varied by changing the line pressure of the machine. The crimp pressure was measured using Pressurex film® and validated using Topaq® analysis (in a similar manner to that shown in Barbagallo *et al.* [17]). The methodology employed for the testing consisted of four phases (cf. Figure 2). The first phase was to produce a benchmark series of results to generate an operational window for time, temperature and pressure for each film, and to conduct integrity tests on the resultant seals. Integrity testing included T-peel pull tests and dyes penetration tests. In the second phase, these limit values of the operation windows were then employed to manufacture the seals using the test crimps. These were also tested for seal integrity. The final phase was to compare, evaluate and report the findings.

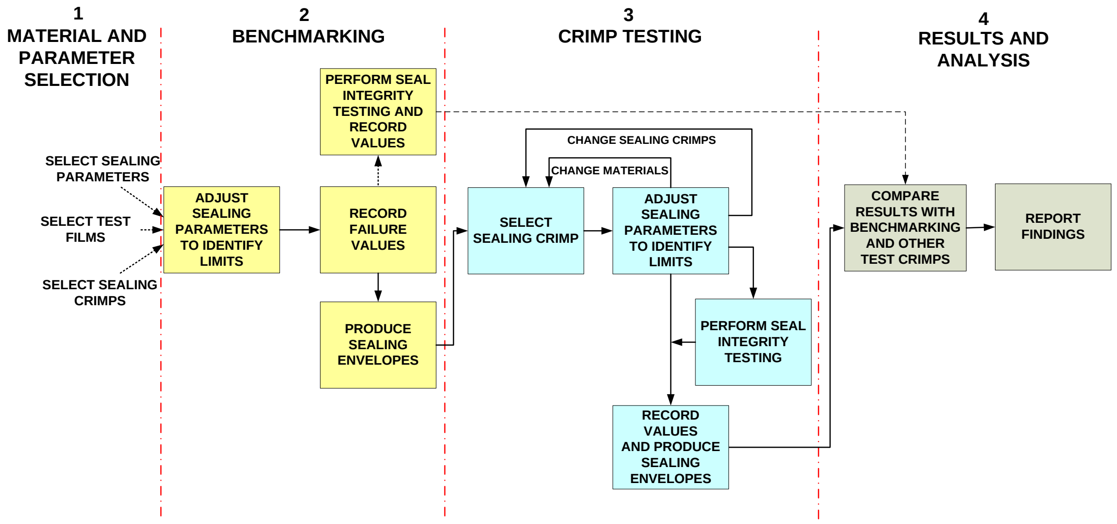


Figure 2 Overall testing methodology

Material and parameter selection

In this study five crimp designs were employed (cf. Table 1). These designs are based on four specific variables (cf. Figure 1): the pitch (*p*), the crimp angle (α), and the top and bottom crimp radii, *r1* and *r2* respectively. The crimps fascias were manufactured to fit to a heated base (bar) unit as shown schematically in Figure 1b. This unit was heated by four 800Watt cartridge heaters. These had been preferentially wound to avoid temperature differentials across the sealing zone [3]. The details of the crimp fascia geometries are shown in Table 1.

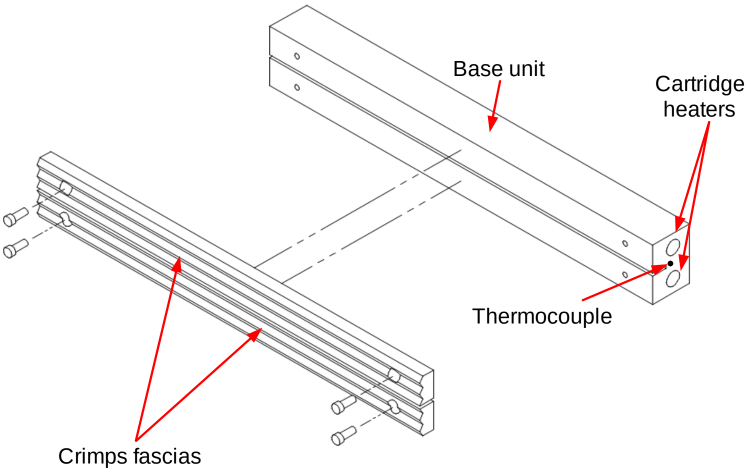


Figure 3 Test sealing crimp setup

The rationale for the selection of these five designs was firstly to investigate the effects of changes in crimp angle. Crimps JS04, JS10 and JS15 permit the change in angle keeping the pitch constant (2mm), and secondly, it was to investigate the change in pitch while keeping constant the crimp angle (90°) using crimps JS07, JS10 and JS12. It was important to use crimp JS10, as investigations of food packaging companies by the authors identified this design as the most widely employed, and therefore provides an industrial benchmark.

Table 1 Sealing crimp geometries

Name	α (°)	*p* (mm)	Radius (mm) *r1*	Radius (mm) *r2*
JS04	60	2.0	0.2	0.3
JS07	90	1.5	0.2	0.3
JS10	90	2.0	0.2	0.3
JS12	90	3.0	0.2	0.3
JS15	120	2.0	0.2	0.3
Benchmark	90	2.15	0.2	0.2

In this investigation, five sample films were used. These commercially available films were supplied by Amcor Flexibles: two biopolymers, consisting of a C1, cellulose and a C2, polylactic acid, along with three gauges of orientated polypropylene. Details of these films are given in Table 2. The bending stiffness and coefficient of friction (crimp material against film) were also measured to understand if these played any role in the sealability of the respective films.

Table 2 Material data

Name	Material	Manufacturer's sealing range (°C)	Gauge (µm)	Stiffness (N/mm)	Sealing layer µm	Coefficient of friction
Cellulose	Cellulose	130-150	38	51.00	2-3	0.230
PLA	Polylactic acid	85-110	35	43.00	2-3	0.290
20OPP	Orientated polypropylene	115-145	20	18.50	2-4	0.250
35OPP	Orientated polypropylene	115-145	35	19.40	2-4	0.270
50OPP	Orientated polypropylene	115-145	50	22.53	2-4	0.260

Benchmarking

For the benchmarking tests, the mid-points of the range of seal temperatures given by the film manufacturer were taken as the start points (cf. Table 2). The benchmarking tests were performed using a proprietary set of crimps which were supplied with the machine. These had a pitch of 0.071" (1.8mm) and a crimp angle of 90°. The benchmarking test procedure took the following steps:

1. Set pressure to setting 1 (Table 3)
2. Set temperature to midpoint of manufacturer sealing range (Table 2)
3. Set dwell time to 50ms
4. Run machine and evaluate bags
5. If an acceptable bag is produced collect the next 12 and record settings
6. Increase dwell time and repeat steps 4-6 (10 dwell times used between 50-1000ms)
7. Decrease temperature by 5°C and repeat steps 2-6 (until no bag can be made)
8. Increase temperature by 1°C until acceptable bag produced, repeat steps 2-6

9. Invert process steps 2-8 to find upper sealing range
10. Set pressure to setting 2 (Table 3) and repeat steps 2-8
11. Change material, repeats steps 1-10
12. Test seal integrity of bags, record values and the mode of seal failure.

All tests were performed at 23 ± 1 °C, with no product being filled into the produced bags. The results of the benchmark testing are shown in Figure 6 and Table 4.

Table 3 Pressure measured values

Setting	Line pressure (bar)	Crimp pressure (N/m^2)
1	2.0	32.50
2	4.0	107.63

Once the required machine variables were set, a one minute run was conducted to allow the system to settle, then 12 sample bags were produced. During the benchmarking tests an acceptable bag was said to have been achieved if the seal was seen to be visually intact with no seal damage (cf. Figure 4a). A seal was said to have failed if there was an obvious unsealed zone or there was material deformation in the sealing area which would be deemed commercially unacceptable e.g. burnt seal (cf. Figure 4b) or overheated (cf. Figure 4c).

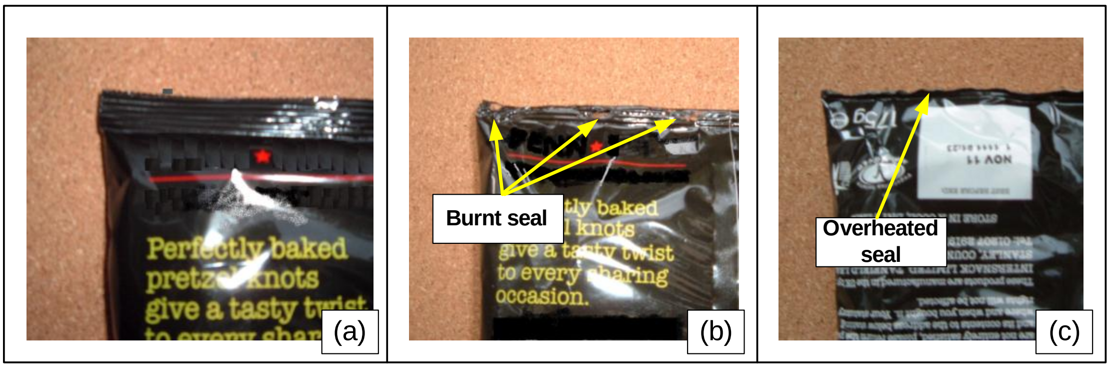


Figure 4 Seal failure examples

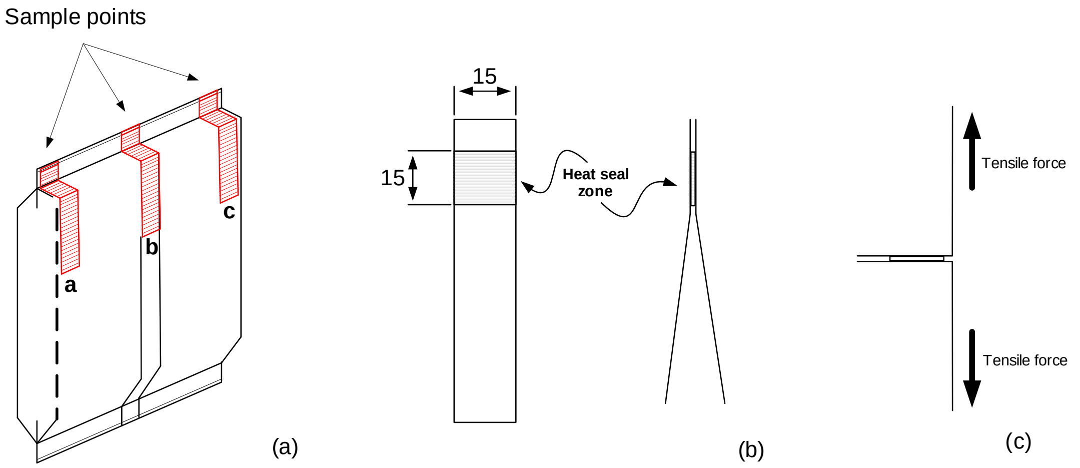
Trials and testing

For the crimp geometry evaluation tests, a similar procedure to that for the benchmarking tests was followed. The main difference was that the lower points of the benchmarking tests became the start points for the testing. The pressure was kept at setting 2 (Table 3), as results from the benchmarking showed it had no effect on the results. Also once a set of tests for an individual material had been completed, the next set of sealing crimps was fitted and the process repeated. These were then used to produce the sealing envelopes, the results of which can be seen in figures 8 and 9. The same criteria, for the evaluation of an acceptable seal, were used as previously employed in the benchmarking tests. At the points where an acceptable bag was produced, 12 sample bags were collected for integrity testing.

Integrity testing

The first integrity test performed was the T-peel. This method is performed by applying a tension load to two flexible materials axially away from each other forming what is called a T-peel (cf. Figure 5c) [18]. This test method is intended for determining the relative peel resistance of adhesive bonds between flexible adherents. From the 12 sample bags, nine were used to produce the test samples (sealed strips) as shown in Figure 5, parts a and b. The T-peel test (cf. Figure 5c) was performed on an Instron tensile tester[19], with a calibrated 50 N load cell. During the testing, a constant rate of loading of 300mm/min with an initial gripper separation of 25mm was selected as recommended by ASTM F88-85[18]. As previous studies [3] have shown that the temperature at which the tests are performed has a significant effect on pull test results and modes of failure, all trials were performed at a temperature of 23 ± 1 °C. The minimum pull force required to pull apart the sample seal, and the mode of failure of each specimen was recorded. The maximum and minimum pull forces values from this series of testing are presented in Table 5.

The remaining three bags were subjected to a dye penetration test[20]. This test is particularly useful if a number of leaks are present. The method employed in this study was to cut the bag in half, paint dye on to all seals on the inside of the bag, stand the bag upright and leave for 30 minutes. A visual inspection of whether the dye had penetrated to the outside of the seal led to a yes/no decision as to whether a leak was present.



(a) (b) (c)

Figure 5 Seal strip manufacture

Analysis and results

While conducting both benchmarking and crimp design testing, several qualitative findings were observed. It was noted that:

- at temperatures of 150°C and above and with crimp angle (α) of less than 90° the PLA showed a tendency to fracture along the trough produced by crimp peak;
- at temperatures of 155°C and above, the cellulose initially sealed but after a few seconds the seals began to re-open;
- at temperatures of 120°C and above, the cellulose had a tendency to stick to the crimp profiles with a crimp angle of less than 90°;
- in the laboratory environment, the PLA was much noisier than the other test films while progressing through the machine’s web handling, conversion and sealing operations in comparison to the other films tested;
- PLA with its higher stiffness required a greater line pressure to fully close the crimps, whereas the other films used in this study all permitted crimp closure at a line pressure of 1 bar.

Benchmarking results

During the benchmarking test, the pressure had been set at two points (Table 3). What became obvious very quickly was that pressure as a factor in the sealing process is irrelevant provided it is sufficient to squeeze the jaws together. Figure 5 presents the sealing envelopes for the five materials using the benchmarking crimps. The parallelogram form in the graphs represent the sealing envelopes (e.g. 1000ms) for each of the materials tested. The values shown on the edges of each envelope are the maximum and minimum dwell times to obtain an acceptable seal. The parallelogram form of the envelopes is to be expected since at lower temperatures (left hand side of envelopes) a greater dwell time is required to transmit enough heat energy into the material to form an acceptable seal. At the right hand end of the envelope, where higher temperatures are used, a much lower dwell time is needed to produce an acceptable seal. It can be seen that these are almost identical. The results of the T-peel tests also show that the maximum and minimum values to produce a “acceptable” bag are also close (Table 4).

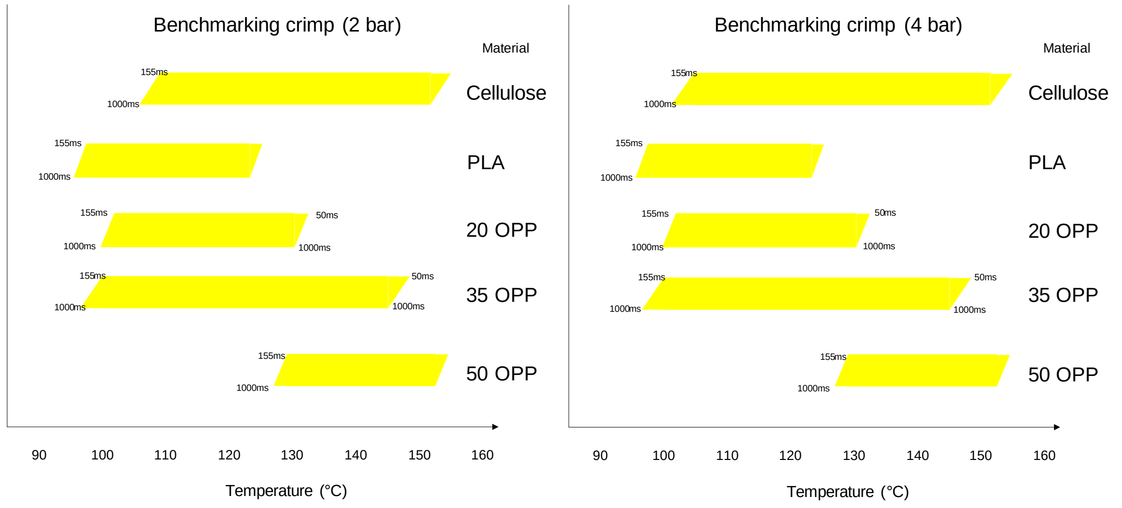


Figure 6 Benchmarking sealing envelopes

Table 4 Maximum and minimum seal strength values for integral bags

Material	**Cellulose**		**PLA**		**20 OPP**		**35 OPP**		**50 OPP**	
Pressure setting	**min**	**max**	**min**	**max**	**min**	**max**	**min**	**max**	**min**	**max**
1	0.60	1.85	1.80	8.10	1.60	10.85	180	8.8	1.50	9.10
2	0.70	2.01	1.60	7.90	1.70	9.95	1.70	10.50	1.50	9.50

Crimp design evaluation

Presented in Figures 7 and 8 are the sealing envelopes for the five materials and the five sealing crimps. Initial observations show that JS04 and JS10 present the largest sealing envelopes for the biopolymers.

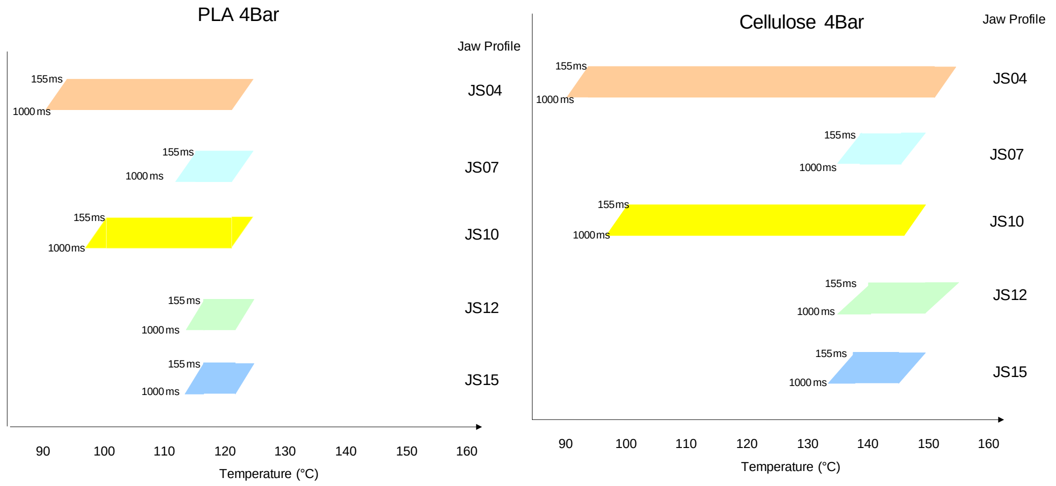


Figure 7 Biopolymers sealing envelopes

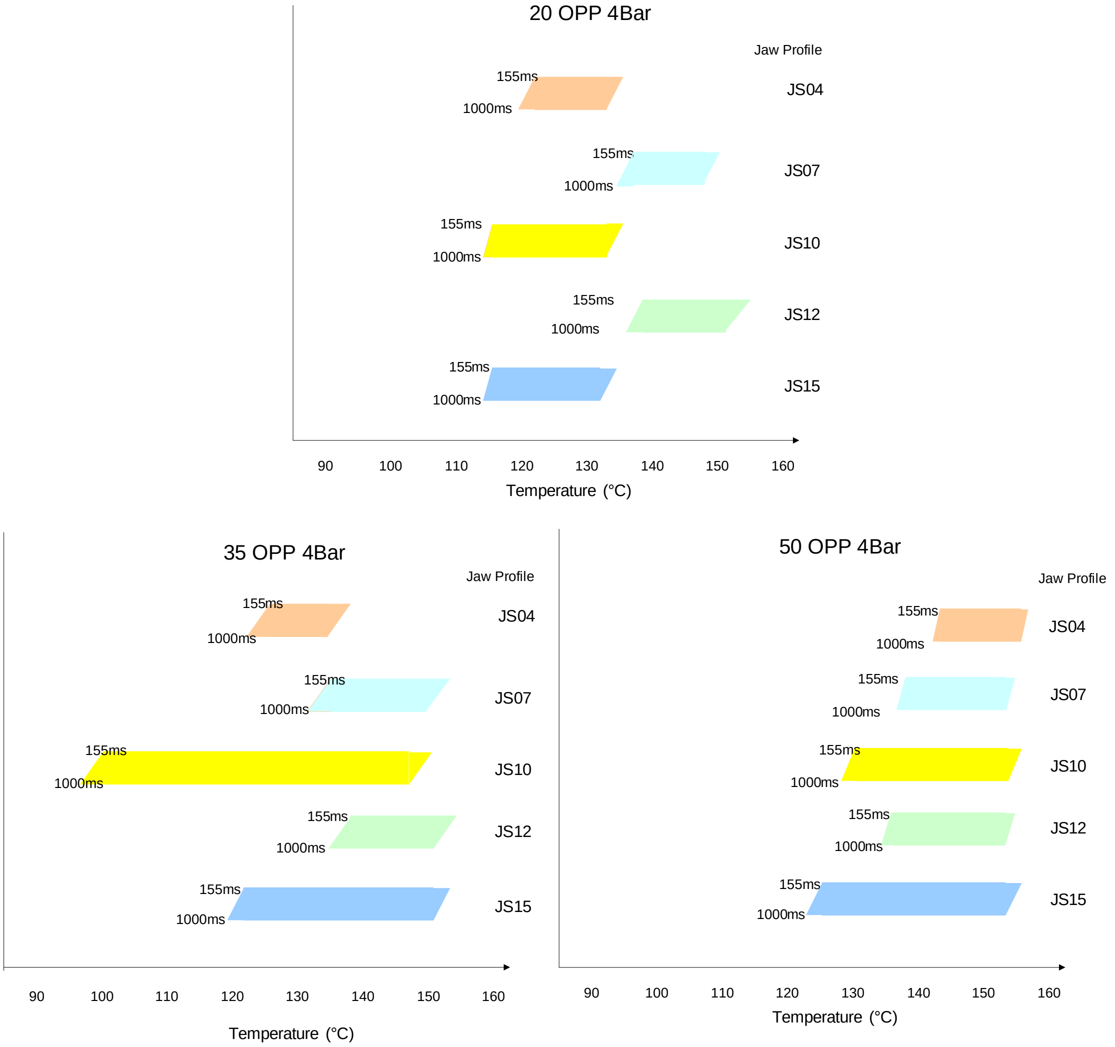


Figure 8 Polypropylene sealing envelopes

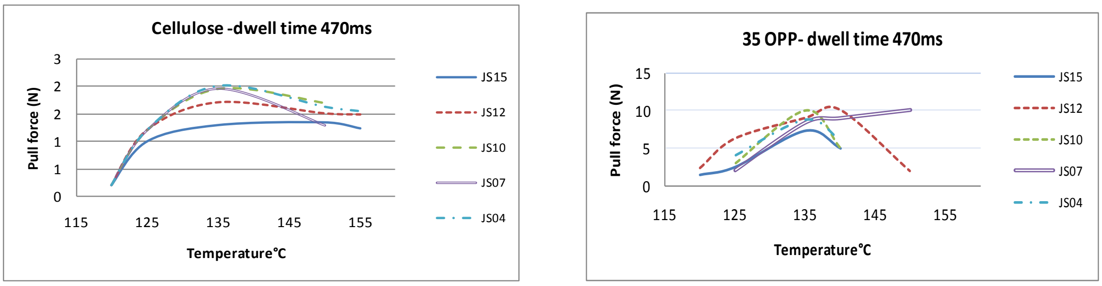


Figure 9 Example heat sealing curves

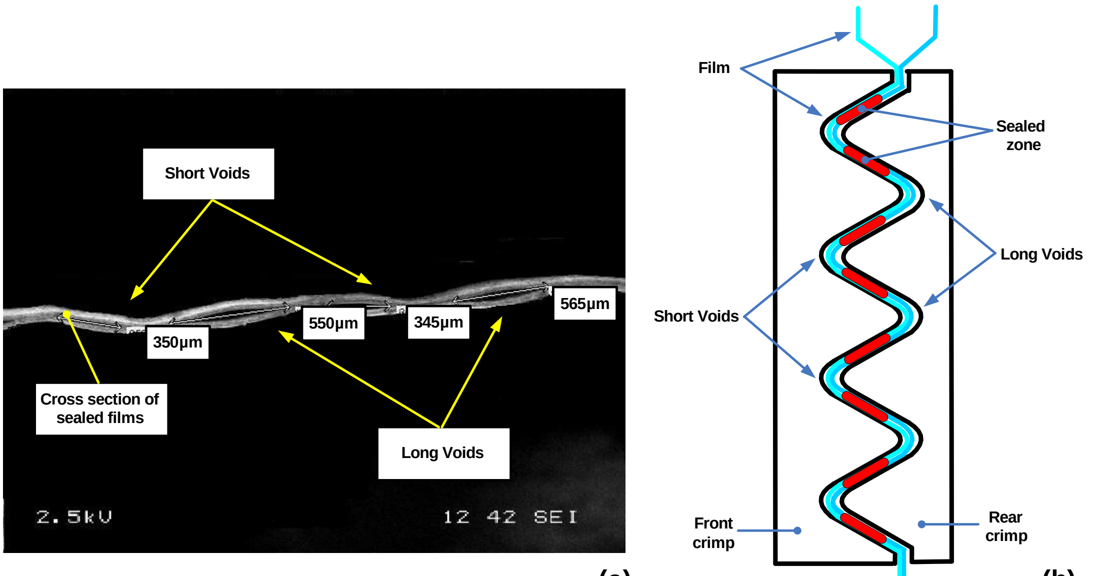
Heat sealing curves for all materials were plotted. These represent the plotted average values from the T-peel tests for different sealing temperatures, two examples are shown in Figure 9. These follow the characteristic rise, plateau and fall off identified by previous researchers [2-5]. Shown in Table 5 is the T-peel maximum and minimum pull force values obtained for the five materials and the five sealing crimps.

Table 5 Maximum and minimum pull force values for integral bags

Crimp	JS15		JS12		JS10		JS07		JS04	
					Pull force (N)					
	min	max	min	max	min	max	min	max	min	max
Material										
Cellulose	0.61	1.46	0.60	1.48	0.60	1.96	1.22	1.96	0.89	1.99
PLA	2.87	7.20	3.18	7.90	1.90	7.60	2.40	7.78	0.79	10.10
20 OPP	2.01	6.28	1.50	9.40	1.90	9.00	3.00	5.50	3.90	6.60
35 OPP	1.62	7.40	2.40	10.10	4.12	10.10	3.40	9.40	4.70	8.8
50 OPP	1.86	6.82	1.10	8.00	1.50	7.40	1.00	13.00	2.00	6.80

ANALYSIS AND DISCUSION OF RESULTS

Investigations into the sealing operation of the test crimps and materials show a variety of characteristics. Initially with all films and crimps, when the temperature and dwell times are at the lower end of the sealing envelope, the films only become sealed in certain zones as shown in figure 10. Part a of the figure shows a scanning electron microscope image of PLA sealed at 102°C and a dwell time of 660ms at pressure setting 2. Part b of the figure shows the “chain” effect of sealed and non sealed areas. It can be seen that the regions of sealed and unsealed areas alternate in length, producing a series of long and short voids in the seal. As the temperature and dwell time increases, the area of sealed film increases until full sealing is obtained. The effect shown in part b is the result of the film layers sealing on the flat sides of the crimp trough, and this is common to all crimps with an angle greater than or equal to 90° and all materials. With the crimp angle at 60°, the films show a tendency to seal on the peaks and trough of the crimp. The reason for this is unexplained and seems to be counter-intuitive.



(a) (b)

Figure 10 Sealing zones

As expected (from previous research), the crimp temperature and dwell time are the dominant variables in the sealing process. This was shown to be true with the results presented in Figure 6 and Table 4. In many form-fill-seal operations, it is the seal strength that is the most important factor [3]. Only in certain operations such as the packaging of products containing nuts, is it important to have a fully hermetic seal. As a metric to compare the effective strengths of seals produced by the five designs, a 75 percentile figure of the peak value obtained during the benchmarking and crimp design tests was measured and shown in Figures 10 and 11. The 75 percentile figure is shown as the dark zones added to the sealing envelopes previously represented in Figures 7 and 8.

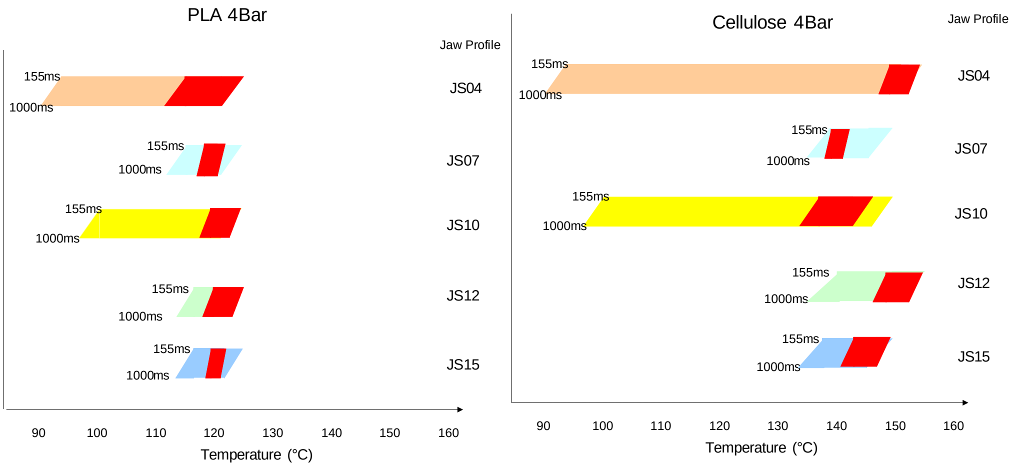


Figure 11 Biopolymer effective sealing envelopes

What is obvious when viewing the sealing envelopes for the test materials and crimp design is that the maximum values are generally obtained close to, or at, the peak seal temperature and dwell time configurations.

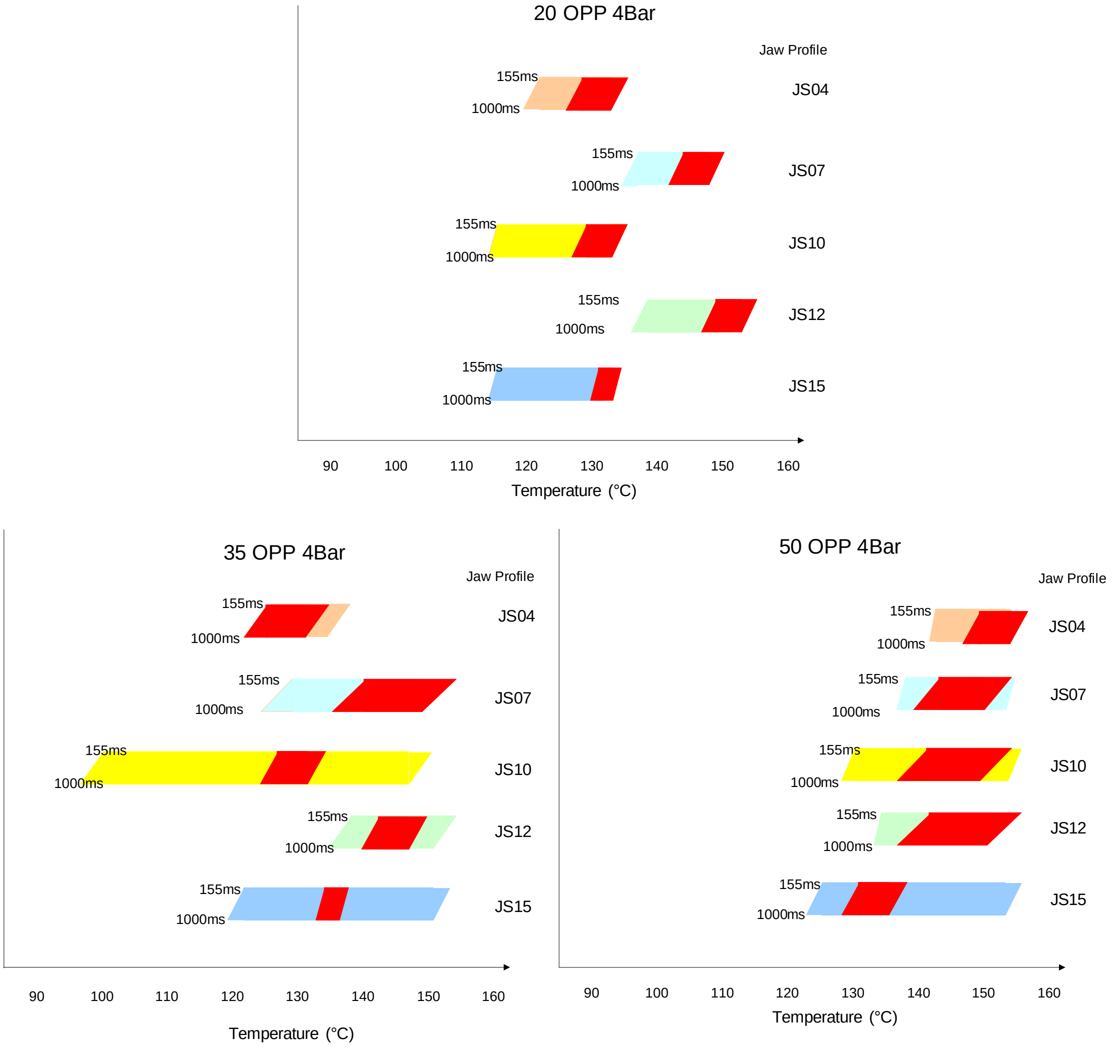


Figure 12 Polypropylene effective sealing limits

In the modes of failure from the T-peel test, the results are common for all materials. At lower temperatures and dwell times the seals failed by interfacial peeling. As the temperature and dwell time increased there is generally a small zone where the seals fail by delaminating. After progressing through this delamination zone all films fail by the film breaking or tearing. The higher strength seals produced in this study all failed by the film breaking or tearing mode. For the OPP films this confirmed the results reported by previous researchers [4,6], at high sealing temperatures, i.e. above 150 °C, the orientation in the film becomes “relaxed” resulting in the consistently lower mechanical properties at this temperature range. The results from the dye penetration test showed that all films failed this test for all crimps, until the temperature had been reached where the seals starts to deform, and becomes one homogenous mass (cf. Figure 9). At this point the seals have become commercially unacceptable. It therefore appears that the dye penetration test is a poor technique to evaluate the materials and crimp designs.

The sealing envelopes presented in Figures 6-8 and 11-12, only reveal part of the story. What is also interesting is the relationship between the crimp angle (α) and material gauge, and the pitch (p) against material gauge on the resultant seal integrity. To this extent, Figures 13 and 14 present these process variables in a surface plot (part a) and in contour plot (part b). These are results for a dwell time of 360ms (a common time for industrial applications [6]).

What can be seen in Figure 13 is that utilising a crimp angle (α) greater than 85° gives the greatest seal strength. With material gauges less that 25 µm, a crimp angle of greater than 110° offers the greatest potential for higher seal strengths. It can also be seen that when using films of gauges, outside the range of 25-45 µm, a crimp angle less than 85° produces relatively weak seals.

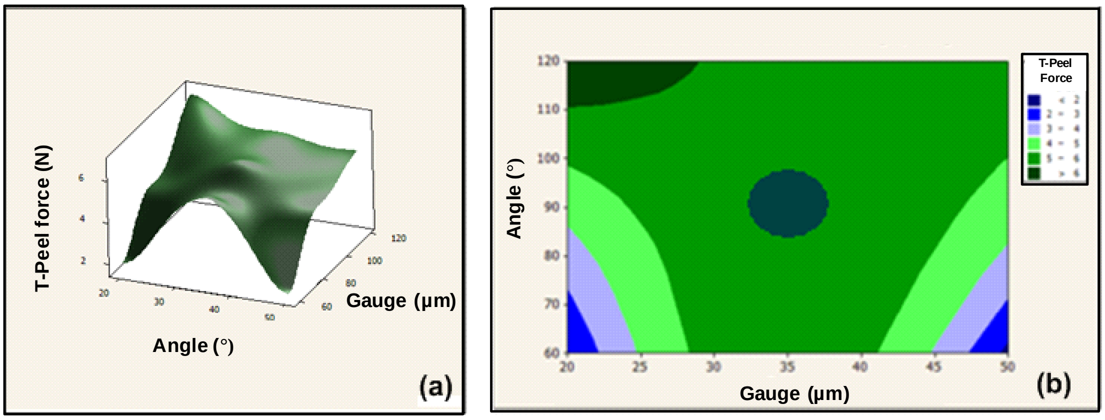


Figure 13 Crimp angle and gauge for OPP

When considering the effect the pitch has on the resultant seal it can be seen that, apart from heavier gauges of material greater than 45µm, the process is insensitive to changes in pitch.

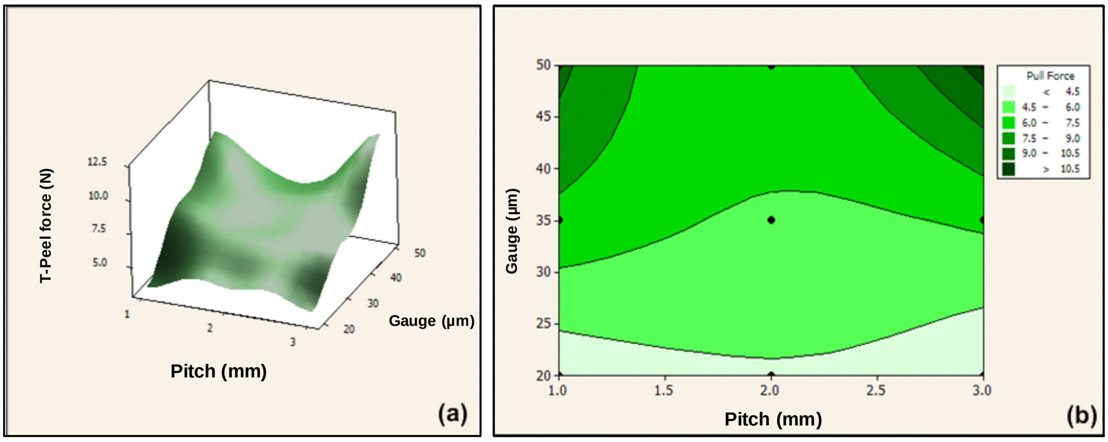


Figure 14 Crimp pitch and gauge for OPP

The results from these studies show the biopolymers exhibit similar characteristics in operation and sealing. It is assumed that the findings of changes in crimp angle against material and changes in pitch against material gauge for the OPP films can be extended to the biopolymers.

IMPLICATIONS

An ongoing objective for almost all industries is to increase process effectiveness i.e. less in-process package failures. This not only saves costs in respect of the volume of packaging consumed, but also the cost of the actual product being packed, which in many food applications has to be scrapped. In achieving this, it is important to make the packaging system more robust and less sensitive to small changes in packaging materials e.g. gauge or mechanical properties and to random changes in process settings. In the context of sealing, this involves the selection of a crimp design that provides a large sealing envelope while still providing integral high strength seals. With this as a consideration, some of the findings of this research have shown that crimp geometries with a pitch of 2mm and crimp angle of 90° are most appropriate for the polyolefin films (which, as noted earlier, is the most commonly employed crimp design). For the biopolymers, crimp geometries with a pitch of 2mm but with a decrease crimp angle to 60°, become most appropriate.

The seal initiation temperature is an important property of film packaging, as a lower seal initiation temperature results in lower energy costs and a broader sealing envelop in a production envieonment[15]. As the seal crimp is the main interaction with the film it was interesting to note that its geometry did play an effect in the ability to produce an acceptable seal at the lowest temperature. In the tests using PLA, crimp geometry JS04, and for cellulose JS10 produced the lowest initiation temperatures for acceptable seals. When using OPP of 35µm and below JS10 and JS04 were found to give acceptable seals at the lowest initiation temperature. But, for OPP of 50µm crimp geometry JS15 was the most effective.

Currently world consumer demands are driving research and development for alternatives to the oil-based packaging materials including those with recyclable or edible properties, as well as those materials made from renewable/sustainable agricultural products [10]. The investigation presented in this paper along with others [8, 12] provides an understanding of how such materials perform during conversion into packaging and how they perform to protect and present the product. In this study, cellulose and PLA showed similar operating characteristics to polypropylene, but in all tests a lower seal strength was achieved, although the seal strength values obtained show that it is suitable for some food applications. While this helps increase confidence in biopolymer solutions, at present it is the additional cost of the biopolymers remains one of the main hurdles to their wider adoption.

CONCLUSIONS

This paper has presented the results of an empirical investigation into the influence of sealing crimp geometry and process settings on the seal integrity of traditional and biopolymer flexible packaging materials. Five materials: cellulose, polylactic acid and three gauges of orientated polypropylene, were chosen along with five different designs of sealing crimp geometry. The findings show a common relationship between the seal strength and its modes of failure. The highest seal strength failed by the mode of tearing, and the lowest seal strength failed under the mode of delamination.

Investigations also showed that the employment of crimp angles greater than 80° offers the greatest potential to gain higher seal strengths with films of gauges outside the range of 25-45µm. The findings also showed that the crimp pitch is not a dominant control factor for films with gauges between 25µm and 40µm, and it is temperature that is the dominant variable. When using cellulose films, a higher seal strength is achievable when both pitch and crimp angle are smaller (p<2mm and α<90°). The results also showed that PLA has a higher seal strength with crimps of a smaller angle (α<90°), although visual inspection showed that such designs also cause small fractures in the sealing area. This paper has also presented some environmental and utilisation implications for users of such films and crimp geometries.

The paper has shown that, the crimp geometry is only a secondary factor in the heat seal cycle. But, in order to obtain an optimal integral seal or reduced process sensitivity with the largest sealing envelope, the selection of the correct geometry (angle and pitch) to match the material gauge is a requirement.

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References

1. European Council, Council Directive 99/31/EC on the landfill of waste, *Official Journal of the European Communities* **L 182** (1999), 1-19.
2. Foster, S, *Domestic Mixed Plastics Packaging Waste Management Options*. WRAP, Oxford, UK, 2008, 1-78. ISBN: 1-84405-396-2.

3. Miyagawa H, *Heat sealing technology and engineering for packaging: principles and applications.* DEStech publishing. Pennsylvania, USA. 2009. ISBN: 978-1-932078-85-0.
4. Theller HW, Heat sealability of flexible web materials in hot-bar sealing applications. *J. Plast. Film Sheet* 1989; **5**: 66-93.
5. Meka P, Stehling FC, Heat sealing of semi-crystalline polymer films, I. Calculation and measurement of interfacial temperatures: effect of process variables on seal properties, *Journal of Applied Polymer Science* 1994; **51**(1): 89-103.
6. Aithani D, Lockhart H, Rafael A, Transparent K. Heat sealing measurement by an innovative technique. *Packaging Technology and Science* 2006; **19**: pp 245-257, DOI:10.1002/pts.728.
7. Tsujii T, Ishiaku US, Mizoguchi M, Hamada H, The effect of heat sealing temperature on the properties of OPP/CPP heat seal. I. Mechanical properties. *Journal of Applied Polymer Science* 2005; **97**: 753-760, DOI: 10.1002/app.21320.
8. Meka P, Stehling FC, Heat sealing of semi crystalline polymer films. II. Effect of melting distribution on heat-sealing behaviour of polyolefins. *Journal of Applied Polymer Science* 1994; **51**: 105-119.
9. Matthews J, Hicks BJ, Mullineux G, Goodwin J, Burke A, Modelling the material flow and web tension in the vertical form-fill-seal packaging process. *Packaging Technology and Science*, to appear, DOI: 10.1002/pts.949.
10. de Oliveira, L. M. and de Assis Fonseca Faria, J. (1996), Evaluation of Jaw Profile on Heat Sealing Performance of Metallised Flexible Packages. Packaging Technology and Science, **9**: 299–311.
11. Weber CJ, Haugaard V, Festersen R, Bertelsen FG, Production and applications of biobased packaging materials for the food industry. *Food Additives and Contaminants* 2002; **19**: 172–177, DOI: 10.1080/02652030110087483.
12. Ruban SW, Biobased packaging - application in meat industry. *Veterinary World* 2009; **2**(2): 79-82.
13. Farris S, Cozzolino CA, Introzzi L, Piergiovanni L, Effects of different sealing conditions on the seal strength of polypropylene films coated with a bio-based thin layer. *Packaging Techology and. Science* 2009; **22**(6): 359-369, DOI 10.1002/pts.861.
14. Su J-F, Wang X-Y, Yuan X-Y, Li M, Xia W-L, Feng, C-L, Heat-sealing properties of soy protein isolate/polyvinyl alcohol blends: effects of the heat-sealing temperature. *Journal of Applied Polymer Science* 2010; **115**: 1901-1911.
15. Farley JM, Meka P, Heat sealing of semi-crystalline polymer films III. Effect of corona discharge treatments of LLDPE. *Journal of Applied Polymer Science* 1994; **51**: 121-131.

16. Yuan CS, Hassan A, Ghazali MIH, Ismail AF, Heat sealability of laminated films with LLDPE and LDPE as the sealant materials in bar sealing application. *Journal of Appied. Polymer Science* 2007; **104**: 3736-3745, DOI:10.1002/APP.25863.
17. Barbagallo, LJ, Shen G, Jones AA, Swain MV, Petocz P, Darwndeliler M, A novel pressure film approach for determining the force imparted by clear removal thermoplastic appliances. *Annals of Biomedical Engineering* 2008; **36**(2): 335-341, DOI:10.1007/s10439-007-9424-5.
18. ASTM, *Standard method for seal strength of flexible barrier material*: *designation F 88-07*. American Society for Testing and Materials, 1987. DOI: 10.1520/F0088-07A.
19. Instron, *Materials Testing Solutions*, //http://www.instron.us/wa/home/default en.aspx, (accessed July 2011).
20. Potter L, Lloyd, E, Campbell A, *The manufacture and integrity of seals for packaged foods*. Campden BRI, Chipping Campden, UK. 2006, 1-30. ISBN: 0-905-42-82-5.