Comparative Evaluation of Hot Air and Ultrasonic Sealing in Paper Cup Manufacturing

Juho Bonifer,* Antti Pesonen, Panu Tanninen, and Ville Leminen

Consistent heat sealing is a critical aspect of paper cup manufacturing, ensuring both liquid tightness and a visually appealing finish. Given the high production volumes in the disposable cup industry, optimizing energy consumption while maintaining good seal quality is critical to minimize waste and resource use. A mechanical testing device for quantifying the side seal strength of finished cups was developed to replace the subjective hand-peel method. Unlike laboratory testing with pre-sealed samples, the proposed test method accounts for stresses imposed on the seal area during the converting process. The device allowed for the objective comparison of cup side seals produced from two different materials sealed using two different technologies: ultrasonic and hot air. The experiments yielded largely consistent results and offered insights into material-specific behaviors in the cup manufacturing process, which involves shorter heating, cooling, and forming cycles than those in other coated paperboard conversion processes. In addition, ultrasonic sealing was shown to have an advantage in sealing consistency over hot-air sealing. The developed test method showed potential as a repeatable evaluation tool for side seal strength in finished paper cups, facilitating quality control across high-speed production lines.

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INTRODUCTION

Paperboard is often regarded as a more environmentally friendly option for packaging applications compared to fossil-based materials, as it is primarily bio-based, potentially biodegradable, and/or recyclable. However, paper and paperboard inherently possess weak barrier properties against liquids and oils and lack sealing capabilities. Therefore, a polymer-based coating is typically required for packaging purposes (Rhim and Kim 2014; Schoukens *et al.* 2014).

Heat sealing plays a critical role in most packaging solutions, ensuring structural integrity and protecting contents from contamination. In paper cups specifically, heat seals are used to shape the cup wall and ensure the container's liquid tightness (Bonifer 2023). Insufficient sealing can lead to aesthetic defects or leakage, which, in the case of hot takeaway beverages, could even pose a safety risk to consumers. The longitudinal side seal—joining the ends of the wall blank, which refers to the cut piece of material that will be formed into part of the cup—is generally a simple lap seal, while the bottom seal is formed between the coated surfaces of the wall and punched bottom blank. Both these seals are produced using heat in a relatively straightforward process that requires:

1. Sufficient heat, delivered *via* convection, conduction, or friction, to melt the polymer acting as a sealant;
2. Pressure to ensure proper wetting and potential penetration of the sealant into any porous surfaces; and
3. Adequate time for the molecular chains to entangle (Mihindukulasuriya 2012).

Challenges may arise when any of these conditions are difficult to achieve—for instance, owing to the weak thermal properties of certain polymers or short dwell times, as often seen in cup-forming processes.

Paper cups are manufactured from wall blanks and a bottom reel in a process operating at production speeds of 50 to 330 cups per minute (CPM). The manufacturing process and its key influencing factors have been detailed in a prior study (Bonifer 2023). Depending on the design of the production machinery, the side seal may be subjected to mechanical stresses immediately after bonding—sometimes before it has fully cooled. The seal strength during this period is known as the hot-tack strength, which is lower than the ultimate seal strength achieved after full recrystallization (Kanani 2021). Selecting the appropriate sealing temperature, based on the coating polymer and production speed, is essential to avoid problems related to hot-tack failure (Kanani 2021).

As mentioned earlier, typically, paper cups are made from paperboard coated on one or both sides with a polymer to provide the necessary barrier properties and heat sealability. The required barrier performance depends on the nature of the contents and whether the cup is intended for takeaway use or longer shelf life. Heat sealability is primarily influenced by the choice of coating polymer, which in paper cup applications is typically low-density polyethylene (LDPE) owing to its excellent barrier properties, low melting point, and good convertibility (Schoukens *et al.* 2014; Rastogi and Samyn 2015). Other influencing factors include processing parameters (pressure, heat input, dwell time), the moisture content of the paperboard, and the degree of surface wetting (Tutunjian *et al.* 2020).

Many cup-forming machines operating at low to medium speeds (50 to 180 CPM) are equipped with ultrasonic welding units in addition to hot-air sealing for side seams. The ultrasonic sealing option is seemingly excluded at production speeds above and matching 200 CPM, most likely owing to the additional activation and dwell time required. The general construction of cup machines at these speeds also differs from the one used in this research paper: the separate side sealing station is omitted in favor of clamps which hold the side seal under pressure during bottom forming, as can be seen in the transition from Newtop-168S (180 CPM) to Newtop-258S (260 CPM), for example (New Debao Machinery, Zhejiang, China). At 140 CPM, the maximum production speed of the machine used for this study, the time available for ultrasonic heat generation and cooling is only ~0.2 s, as determined through high-speed video analysis of the process (Bonifer 2023).

Ultrasonic sealing works by converting electrical signals into mechanical vibrations that generate localized heating (Tutunjian *et al.* 2020) at the interface, thereby producing a welding effect. The initial heat generation results from frictional forces (Selke and Culter 2016; Charlier *et al.* 2021) and is influenced by the material's coefficient of friction until the polymer reaches its glass transition temperature (T_g), after which viscoelastic heating causes a rapid temperature increase (Zhang *et al.* 2010; Levy *et al.* 2014). This rapid rise in temperature enables the polymer coating to wet the interface and promote bonding. The process is particularly important for single-sided coated materials, where the coated surface must deliver the sealant and bond to the uncoated fiber or pigment-coated side.

A key advantage of ultrasonic sealing in cup production is that it does not rely on molten polymer while the blank is transferred to the mandrel, thereby avoiding damage to softened coatings and reducing friction-related issues (Rastogi and Samyn 2015). Previous studies have shown that ultrasonic side seals are approximately 15% thinner than both unheated, compressed samples and hot-air-sealed counterparts (Regazzi *et al.* 2019; Hofmann and Hauptmann 2020). This is likely due to greater material compression caused by ultrasonic vibrations, which may also enhance wetting by collapsing pores and increasing interfacial contact area.

Manufactured cups are assessed based on their visual appearance and performance in various tests, although few of these are standardized (Bonifer 2023). Each manufacturer typically uses their own testing protocols, which may include liquid tests with hot coffee, ethanol, or dyed soap water, as well as manual peel tests to evaluate seal integrity. The ASTM F88/F88M standard (2023) describes a method for measuring the seal strength of flexible barrier materials. However, this method does not adequately simulate hand-peel testing and requires specific test specimens, rendering accounting for stresses introduced during later stages of the manufacturing process difficult. Moreover, preparing a test specimen from a preformed cup without damaging the seal is both challenging and time-consuming. The use of test specimens also does not consider the additional stresses introduced early in the manufacturing sequence, after side sealing occurs. Furthermore, the standard specifies 90° or 180° peel angles, while the actual peeling angle for finished cups is considerably smaller (ASTM F88/F88M 2023).

In general, seal strength increases with temperature up to the polymer's melting point, beyond which further heating offers no significant benefit (Yuan *et al.* 2007; Milner 2011). However, in the cup-forming process, the dwell time is shorter, and blank feeding is more erratic than in typical heat sealing studies—likely introducing process-related inconsistencies. Studying heat sealing under conditions comparable to industrial production is critical to fully understand how parameters and material properties interact.

The primary objective of this study was to validate the applicability and accuracy of a developed seal strength analysis device by comparing ultrasonic and hot-air sealing methods within a commercial paper cup manufacturing system. Both methods were applied using the same equipment under comparable conditions; hence, the study also enabled the collection of meaningful data on the differences between the two sealing techniques despite the inherent variability of a high-speed converting process. A secondary objective was to analyze the strength of seals formed at temperatures above those required for full-fiber tear (cohesive failure) to evaluate the impact of excessive heating on seal quality. An objective, repeatable method for evaluating the sealing performance of finished cups could help reduce energy consumption and reduce the number of defective cups through parameter optimization.

EXPERIMENTAL

Materials

Two commercial single-sided extrusion-coated cupstocks, along with bottom substrates of lower basis weight coated with the corresponding polymers, were used to manufacture the test cups (Table 1). The first cupstock (C1) was coated with polyethylene, whereas the second (C2) featured a bio-based polymer coating. The coated side of both materials was the inner surface of the finished cups. C1 was selected due to the widespread use of similar polyethylene-coated materials in the market, whereas C2 represents ongoing efforts to replace fossil-based materials with more sustainable, bio-based alternatives. As both materials were coated using the same extrusion coating process, their comparison was considered relevant and meaningful.

The cupstocks were cut into blanks using a flatbed die cutter in the packaging laboratory at LUT University. All materials were conditioned and tested in a constant climate at 23 °C and 50% relative humidity. The key material properties relevant to this study are presented in Tables 1 and 2.

Table 1. Grammage and Thickness of Used Tested Materials

Material	Grammage (g/m^2)	Coating Grammage (g/m^2)	Thickness [a] (μm)	Coating Thickness (μm)
C1	248.1	15	336	10
C2	258.5	25	352	20

[a] The cup machine manufacturer guarantees good dimensional accuracy of cups for materials within a range of 340 ± 15 μm.

Table 2. Key Mechanical Properties of Used Test Materials

Coating Side Friction (coefficient)		Board Side Friction (coefficient)		Bending Resistance (mN)		Tearing Resistance (mN)	
MD [a]	CD [b]	MD	CD	MD	CD	MD	CD
0.509	0.512	0.215	0.213	226	89	2270	2370
0.262	0.259	0.203	0.202	257	111	2290	2610

[a] Machine direction; [b] Cross direction

Design Process of the Side Seal Strength Analysis Device

The integrity and quality of cup side seals are often tested using a hand peel test, in which the rim roll of the cup is undone, the joined surfaces are grabbed individually, and a peeling motion is performed to separate the surfaces from each other. A satisfactory result would be a full fiber tear along the full length and width of the seal area. However, as these tests are performed manually, different peeling techniques may affect the results. In addition, the test results are mainly visual, and the resulting seal strength is interpreted subjectively; thus, it is easily affected by bias. Previous observations have shown that even if different peel testers attempt to reproduce the same peeling action, differences in hand dexterity and finger strength affect the results. To counteract this problem, a device was designed to reliably open the seal in a similar manner. The final device and forces involved in the testing procedure are shown in Fig. 1.

The cup to be tested is pressed onto a mandrel that matches the inner dimensions of the cup and contains a peeling tool nested inside the mandrel at the starting position. A force (F_t) is applied using a universal tensile tester to push the device downward. When the die and cup are pressed onto the base of the testing device, the support plate supports the weight of the device and the cup (F_s) and peeler pushes the outer layer of the lap seam away from the inner layer. This creates a force that restricts the movement of the universal tensile tester (F_p). A curved peeling tool profile is used to direct the peeling motion downward, instead of outward when a straight peeling tool is used. A single test comprises a pretest stage and a test stage, which begins when the support force reaches 15 N, after which a downward force is applied for a stroke length of 36 mm at a speed of 150 mm/min.

The maximum force and energy expended in opening the seam during the test stage are recorded using a universal tensile tester. The device attached to a Shimadzu AGS-X 10 kN universal tester (Shimadzu Corporation, Kyoto, Japan) along with the base plate is presented in Fig. 2.

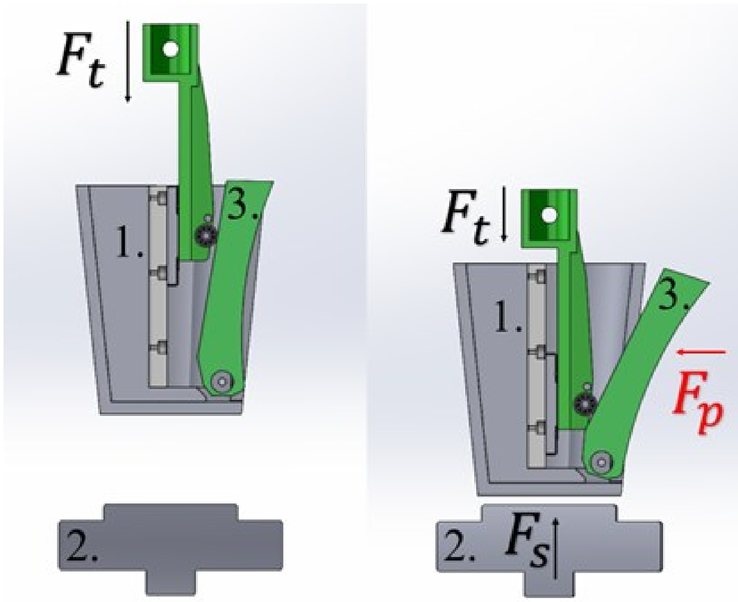

Fig. 1. Cup peeling device: 1. Mandrel, 2. Support plate, 3. Peeling tool

Fig. 2. Finished seal strength analysis device attached to the universal tester

Cup Manufacturing

The cups required for testing were manufactured using a commercial Debao NewTop 138s high-speed cup forming system (New Debao Machinery, Zhejiang, China) at the packaging laboratory of LUT University. The cup manufacturing process was conducted in a manner similar to that used in a previous study (Bonifer *et al.* 2024), where the process is described in detail. Any necessary changes made to the tests in this study are introduced in subsequent sections.

Hot air sealing

Cup manufacturing was conducted for materials C1 and C2 at three production speeds of 60, 100, and 140 CPM. When the production speed was lowered while using hot-air sealing, each blank expended a longer time at the side-seam heaters, resulting in a higher heat input for the same set temperatures. As the nozzles provide a constant stream of hot air, the heating times for 60, 100, and 140 CPM corresponded to the duration of a single machine cycle: 0.47 s, 0.28 s, and 0.20 s respectively. The side sealing temperature range was held constant at 225 °C to 450 °C, in 25 °C increments, for each production speed, resulting in excessively high sealing temperatures (near 450 °C) at the lowest speed and temperatures considered low for cup manufacturing (near 225 °C) at the highest speed. The distance from hot air nozzle to substrate was approximately 10 mm for both sides. The temperature range was selected based on initial hand-peel tests of the cup side seals at 140 CPM, which was the maximum production speed of the machine. The bottom sealing temperature was not varied in this study because its effect on the side seal strength should be minimal. Nevertheless, the lowest possible temperature resulting in a full-fiber tear bottom seal was used to minimize the chance of interference with the bottom portion of the side seal. The bottom-sealing parameters are presented in Table 3.

Table 3. Bottom Sealing Parameters for Both Materials at Different Production Speeds

Material	C1			C2		
Production speed (CPM)	60	100	140	60	100	140
Bottom sealing temperature (°C)	325	375	425	300	350	400

The cups were produced in batches of 30 per test point to ensure at least 10 defect-free cups for the side-seal strength tests. During production, an FLIR A8201sc high-speed thermal camera (Teledyne FLIR LLC, Wilsonville, Oregon, U.S.) was used to record the temperature of the side seal area, the hot air-heated, polymer-coated sealing surface specifically ("C" in the upcoming Fig. 3), for comparison with the set hot air temperature of the machine. As ultrasonic sealing causes localized heating between the seal surfaces only after interfacial contact has been established, the same could not be done for ultrasonic sealed samples. The thermal camera has a sensitivity of 0.02 °C, spectral resolution of 3–5 µm, and maximum refresh rate of 50 Hz at a resolution of 1024 × 1024 pixels. To increase the refresh rate to 135.9 Hz, the resolution was reduced to 512 × 512 pixels.

Ultrasonic sealing

Similar to hot air sealing, ultrasonic sealing for the side seaming stage was conducted at 60, 100, and 140 CPM. The heat in ultrasonic sealing is generated quickly and only during the pressing stage of side sealing; hence, the same activation times can be used at different speeds. One of the goals of this study was to determine the effect of exceeding the threshold for full fiber tears on the strength of the formed seals. The ultrasonic activation times were inversely proportional to the production speed. This ensured that lower speeds would similarly result in extreme seal temperatures (as in hot-air sealing) to evaluate their effects on the side seals. The initial activation time settings were selected in the same manner as those for hot-air sealing: hand-peel tests for cups produced at 140 CPM. Bottom sealing temperatures were unchanged from the hot air sealing trials. Six test points were chosen, the lowest of which was barely sufficient to create some adhesion between the surfaces, whereas the highest was the maximum for a dwell time of 140 CPM (0.20 s). The initial activation and speed-adjusted times are presented in Table 4.

Table 4. Ultrasonic Activation Times at Different Production Speeds

Portion of Dwell Time (%)	Ultrasonic Activation Time (s)		
	60 CPM	100 CPM	140 CPM
45	0.21	0.13	0.09
55	0.26	0.15	0.11
65	0.30	0.18	0.13
75	0.35	0.21	0.15
85	0.40	0.24	0.17
100	0.47	0.28	0.2

RESULTS AND DISCUSSION

Cup Manufacturing and Thermal Imaging

Both materials were successfully manufactured into cups of acceptable quality at all selected test points using both sealing methods.

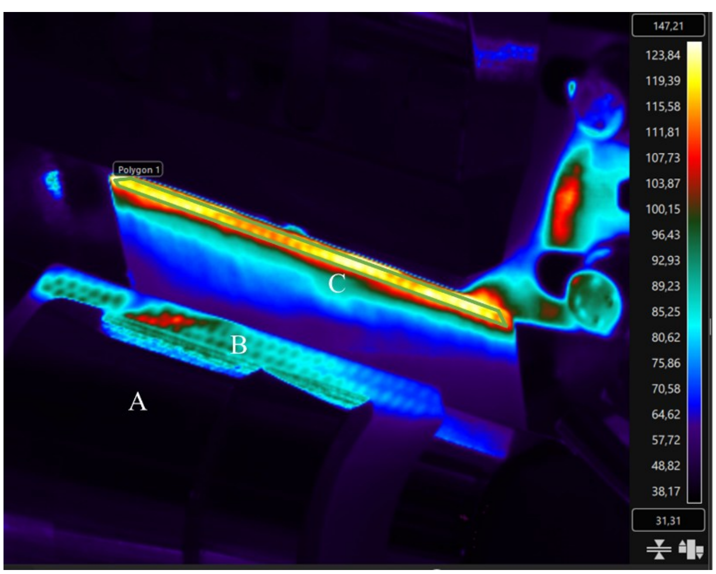

Fig. 3. Thermal imaging of the side sealing process. The measured area on the coating side is defined by the green line (Polygon 1). Components visible in the picture: A = Blank folding wing, B = Outside (fiber) sealing surface, C = Inside (coating) sealing surface. Process direction is toward the right-hand side of the picture

However, material C2 required the installation of a spring-loaded lifting tool during the bottom-knurling stage, as the cups tended to get stuck in the tool. This disrupted the process and prevented the cups from advancing to the rim-rolling stage. Additionally, due to the high heat input from hot-air sealing—possibly causing excessive drying or increased friction—some test runs of C2 at 60 CPM experienced a high frequency of burst rim rolls. Hence, the rim-rolling step had to be omitted for these test points to enable further testing with the seal strength analysis device. The absence of the rim roll did not appear to influence the seal strength results, as the rim of each cup was slightly unrolled in any case.

An FLIR high-speed thermal camera was used to record the temperature of the coated side of the seal surface during all hot-air-sealing test points (Fig. 3). The coated side was selected for temperature measurement as it plays a more critical role in sealing performance than the fiber side. This also ensured consistency across measurements: the blank was supported by the blank track while hot air was directed from above onto the coated surface. The fiber side was only partially supported by a metal bar and heated from below, allowing for more movement.

Side Seal Strength Analysis

Ten cups without manufacturing defects near the side-seam area of the rim roll were selected for testing at each test point. As the goal was to measure the energy expended during the opening of the side seal, any tests resulting in the peeling tool of the device shearing through the cup material were rejected and re-tested. This may have occurred because of a defect in the rim roll or improper cup placement on the mandrel. Figure 4 shows the expected results of the side-seal strength test along with a rejected sample with a partial peel.

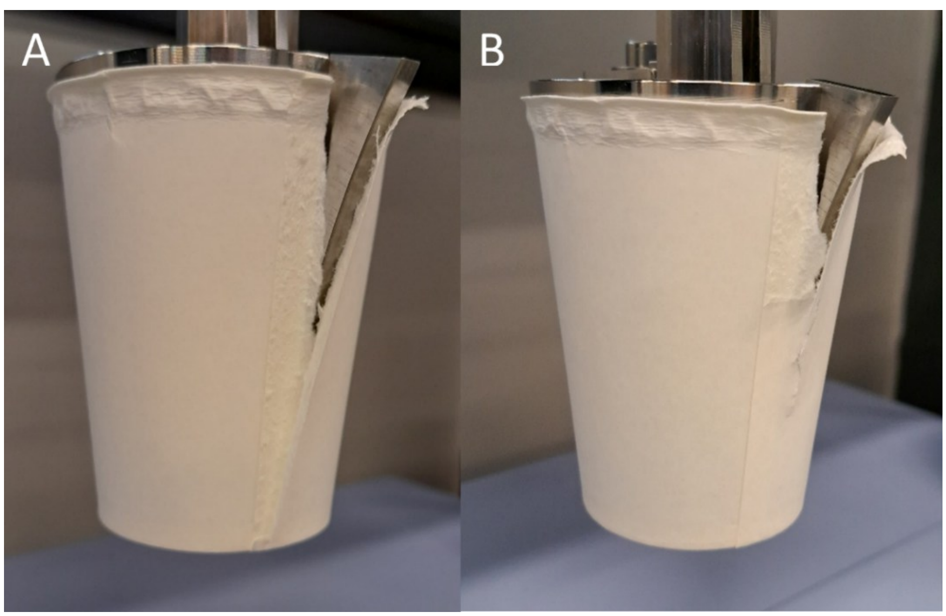

Fig. 4. Intended seal opening mode (A) and rejected test (B) in which the blade has sheared the cup wall

A 10-test series of tests with an empty tool was conducted to record the average energy expended by the moving parts of the device (0.658 J), which was then deducted from the final side-seal opening tests.

Hot air sealed cups

As expected, the energy expended in opening the lowest-temperature seals at the highest production speed was very low; the seals showed little to no fiber tearing, despite withstanding the remainder of the manufacturing process. As the sealing temperature increased, the seal opening energy continued to increase over the entire temperature range, along with a reduction in the standard deviation, until the optimal sealing temperatures were reached. An exception was the 450 °C test point of C2, where the standard deviation increased sharply despite being the strongest seals. This was likely due to one very strong seam (opening energy 39 J) and one very weak seam (opening energy 30 J) in the series.

An overall view of the hot-air seal strength with respect to the set temperature is shown in Fig. 5. Due to the large amount of data points, the bars in upcoming histograms are arranged such that the shorter bars are in the front and taller bars in the back with line density signifying production speed (higher density = higher production speed)

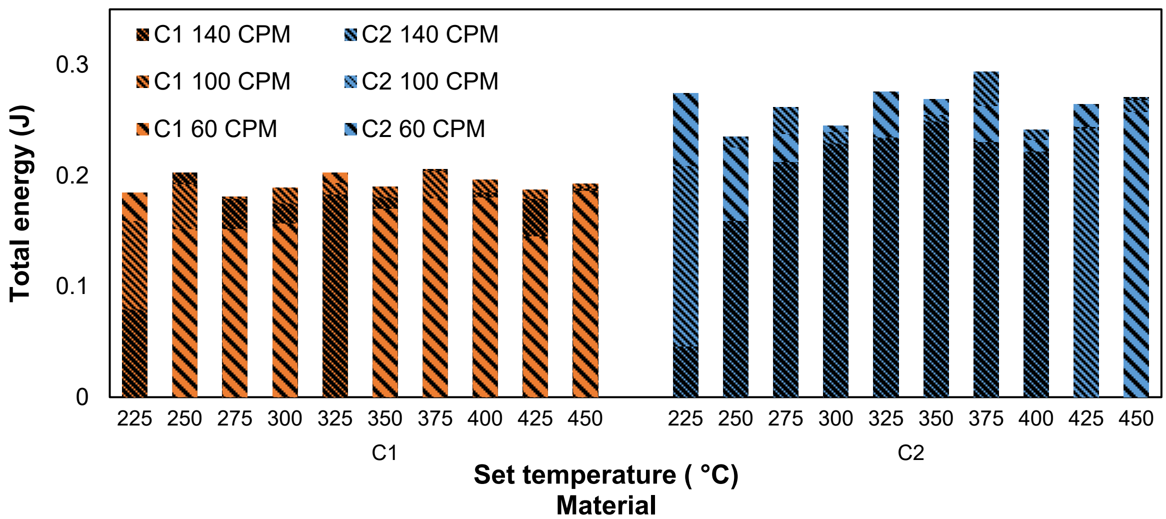

Fig. 5. Seal opening energy of hot air sealed cups. Production speed is visualized by the density of lines on the bars

The seals of the cups produced at 100 CPM generally showed the lowest variation in seal strength. Due to the extended heating time at this speed, the peak seal opening energies for both C1 and C2 were reached before the maximum set temperature of 450 °C. Beyond this point, the opening energy began to decline, accompanied by an increase in deviation. Both materials exhibited a similar "wave-like" pattern in required opening energy, which was more pronounced in material C2.

At 60 CPM, the seal temperature quickly rose to a sufficient level to produce opening energies comparable to those observed at 100 CPM, peaking at 325 °C for both materials. Exceeding this temperature again led to a reduction in seal opening energy and increased variability, as can be seen at 100 CPM. Interestingly, a second increase in opening energy was observed at 450 °C for C1 and 425 °C for C2. This behavior is likely due to increased polymer penetration into the fiber structure, caused by complete liquefaction of the coating. Thermal camera data confirmed this, showing that the first peak corresponded to the melting point (T_m) of the polymer (unknown for C2), while the second peak aligned with temperatures where the polymer reached full fluidity—near 200 °C for both materials.

The coefficient of determination (R^2) values representing the relationship between sealing energy and temperature increases were generally weak across all hot-air test points for both materials, with the exception of C1 at 140 CPM, which displayed a relatively high R^2 value of 0.58. In contrast, ultrasonic sealing of material C1 produced moderate to strong R^2 values at all tested speeds. Overall, material C1 exhibited a more predictable sealing behavior, with consistent trends in seal opening energy across temperatures and speeds for both sealing methods. Detailed results for the relationship between hot-air temperature or ultrasonic activation time and seal opening energy, along with R^2 values, are presented in supplemental Figs. S1 to S6.

During testing, two distinct seal-opening modes 1 were observed, each producing different force curves and tear surfaces, as shown in Figs. 6 and 7. In contrast to the other figures presented, these two plot maximum force on the y-axis to better highlight differences between individual test results.

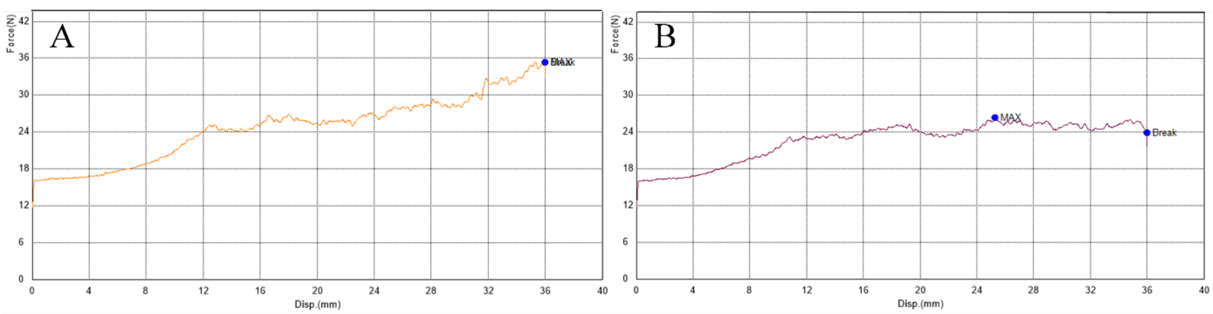

Fig. 6. Force curves generated by a full fiber tear peel (A) and a coating side peel (B)

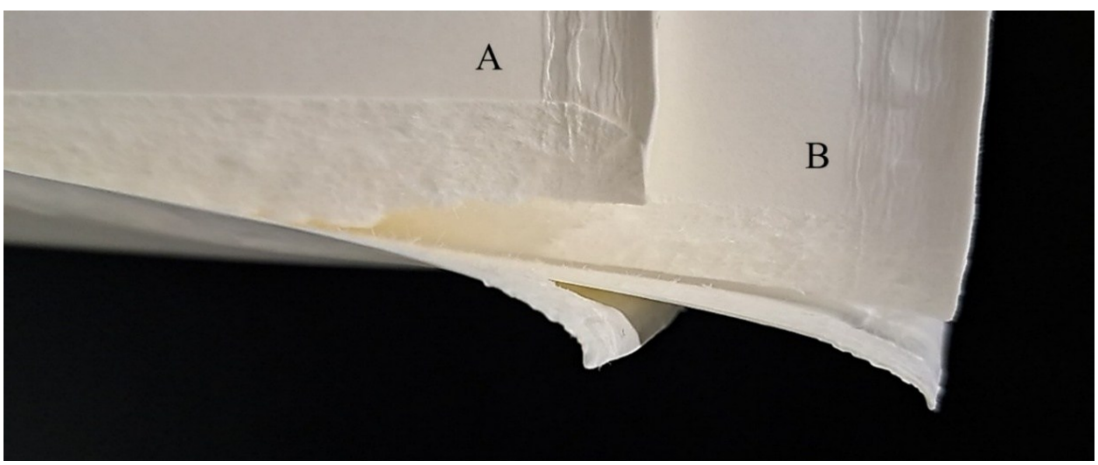

Fig. 7. Corresponding full fiber tear peel surface (A) and coating side peel surface (B).

As shown in Fig. 7, sample A retained more fibers from the opposing coated surface than sample B, as exemplified by the clear boundary between the seal area and the cup's fiber surface, which was missing from sample B. This difference is likely caused by the weaker seal area near the rim roll, which is an area of high stress in the final stages of the forming process. The rest of the seal peels more easily because less material is removed from the outset. Thus, the peel mode of sample A resulted in higher maximum force and energy expenditure. Such differences would not likely be discernible in a hand-peel test, further reinforcing the need for a quantitative test method for seal strength.

Ultrasonic sealed cups

The seal strength analysis tests for ultrasonic cups had a more consistent pattern compared to those of hot-air sealed cups, possibly because hot-air sealing is more prone to feeding inconsistencies and friction-related issues, which are caused by the larger heated coating area, in addition to the blank being moved to the mandrel while the coating is in a molten state. The average seam-opening energies of the ultrasonically sealed cups are shown in Fig. 8.

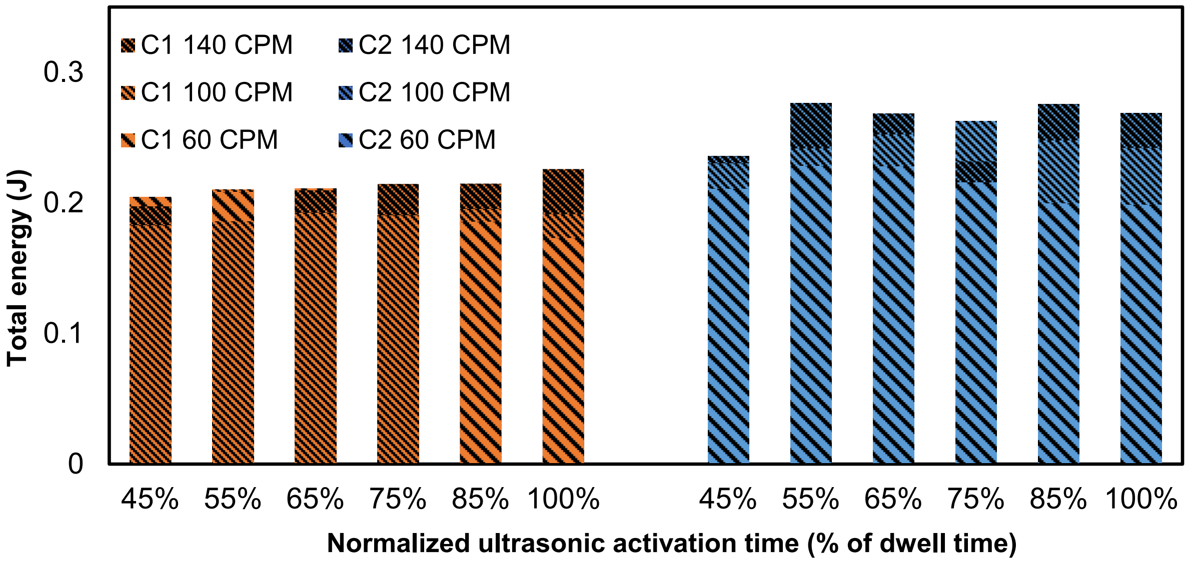

Fig. 8. Average seam opening energies for ultrasonic sealed cups

Based on these results, ultrasonic sealing seems to be more effective than hot air sealing, particularly at the highest speed of 140 CPM, owing to the fast heating immediately preceding pressing. The achieved seal strengths were comparable to those of hot-air sealing at a production speed of 100 CPM, which displayed the highest consistency among the three. The seal opening energies of the cups at each production speed were also more consistent with increases in ultrasonic activation time compared to the temperature progression used in hot-air sealing.

Relationship of seal area temperature and opening energy

In hot-air sealing, comparing only the set temperature to the seal opening energy provides only partial information on the sealing, owing to possible differences in material properties that could affect thermal behavior, including specific heat capacity, thermal conductivity, and structure of the coating polymer

Figure 9 illustrates the relationship between set temperature, seam temperature, and seam opening energy for the hot-air-sealed samples of material C2 at production speeds of 60, 100, and 140 CPM. Peak opening energies were observed at set temperatures of 325, 375, and 450 °C, respectively, corresponding to seam temperatures of 133.8, 136.7, and 153.2 °C. As both the 60 CPM and 100 CPM conditions also showed an increase in energy expenditure near a seam temperature of approximately 150 °C, the deviation observed at 140 CPM may be attributed to feeding irregularities caused by the increased production speed. The figure also demonstrates that an adequate level of seal strength was achieved relatively early, even before consistent full-fiber tearing occurred.

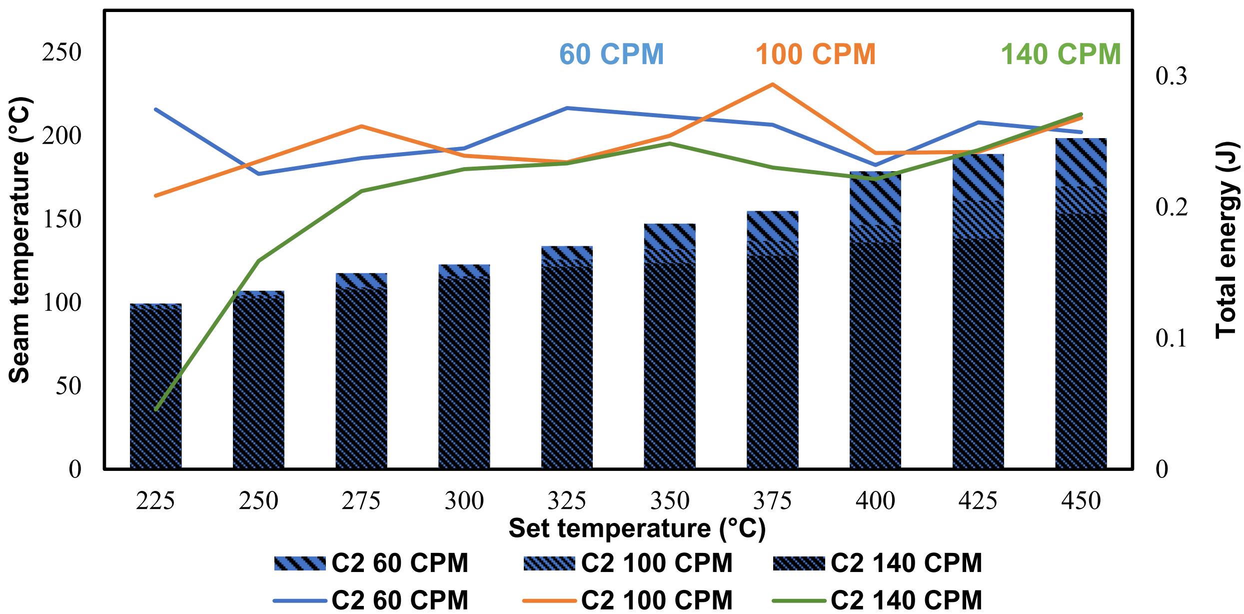

Fig. 9. Relationship between set and measured seam temperature in hot air sealing of material C2 along with peak energies at 60 CPM, 100 CPM and 140 CPM. The seam temperature is represented by the bars while the lines represent seal opening energy.

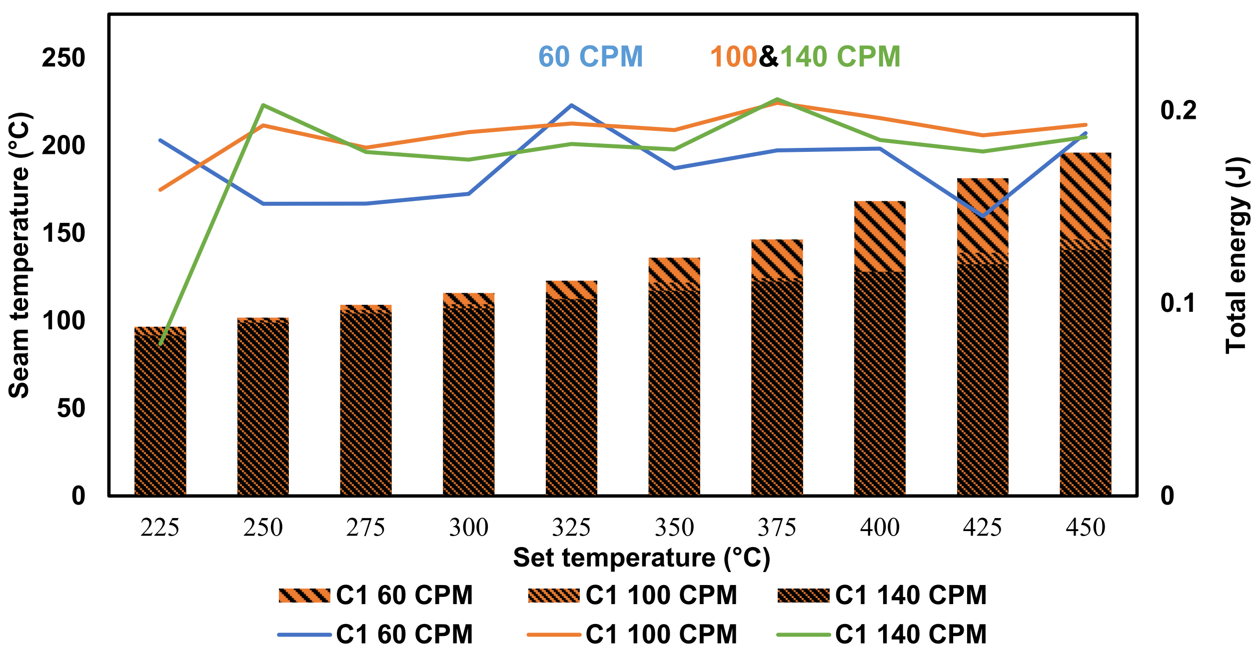

Fig. 10. Relationship between set and recorded seam temperature in hot air sealing of material C1 along with peak energies at 60 CPM, 100 CPM, and 140 CPM. The seam temperature is represented by the bars while the lines represent seal opening energy.

The same relationship for material C1 is shown in Fig. 10. Interestingly, the seam temperatures at 100 and 140 CPM were nearly identical across all test points, despite the increased heating time at the higher speed—an effect not observed with C2. This is further reflected in the peak seam opening energies, which were reached at set temperatures of

325, 375, and 375 °C for 60, 100, and 140 CPM, respectively. Material C1 exhibited more consistent behavior overall, with seam temperatures at peak opening energy varying by less than 2 °C across the three speeds. This stability can likely be attributed to the relatively low melting point and high thermal conductivity of polyethylene, which enable rapid heat transfer, melting, and subsequent cooling.

Overall, the test results obtained with the device were consistent, particularly considering the high-speed and complex nature of the cup manufacturing process. Further developments of the device should include the following:

1. A device may be required to remove the whole rim roll area of the cup before testing without damaging the cup to reduce potential variations in the results caused by the rim unrolling. This would also ignore the effects of failing the rim rolling stage.
2. The rim rolls of some cups had tears or damage of approximately 90° from the location of the side seam. These cups took a shape resembling the one caused by the hand peel method during the tests, owing to more give in the rim roll area. If future testing proves that this is beneficial in terms of consistency, a set of knives to notch the rim roll could be added to the mandrel.

Future test cases should preferably include fewer test points and more parallel samples to minimize the impact of machine-specific and process-related inconsistencies. This was particularly apparent with the slight inconsistencies in the seal opening energies of C2, which could have been caused by the higher melting point and lower thermal conductivity of the bio-based coating polymer.

CONCLUSIONS

1. The objective of this research was to compare the hot air- and ultrasonic sealability of two cup materials coated with different polymers through the development of a consistent and objective side seal test method for evaluating the quality and strength of paper cup side seals, with the potential to replace the commonly used but subjective hand-peel test. Testing finished cups—rather than pre-prepared test pieces—is essential for obtaining accurate results, as the side seal is formed early in the manufacturing process and is subjected to various stresses during subsequent stages.
2. The seal strength analysis device developed in this study demonstrated strong potential for comparing and evaluating heat-sealing process parameters. Moreover, among the two sealing methods compared, ultrasonic sealing showed notable advantages in consistency over hot-air sealing at higher production speeds, without compromising seal strength. This is particularly beneficial given the erratic nature of blank feeding and the limited heating area provided by hot-air blowers. However, ultrasonic sealing is more sensitive to tool clearance and the surface characteristics of the materials used. Additionally, the size of ultrasonic sealing equipment and the extremely high speeds of some commercial machines may limit its applicability.
3. The comparison between set hot-air temperatures, recorded side seal temperatures, and seam-opening energy revealed that the required heat input for achieving adequate seal strength was relatively low. However, cups not displaying very little to no fiber tearing were able to survive the rest of the manufacturing process, further highlighting the importance of monitoring side seam quality to avoid defective products caused by variance, for example. Increasing the temperature beyond this point yielded only minor

reductions in deviation of seal opening energy. Both materials reached 75% of their peak seal strength within a 75 °C increase in set temperature, suggesting that strong seals can be achieved with moderate heat input—provided that blank feeding is consistent and mechanical settings are optimized. Excessive temperatures, on the other hand, led to increased energy consumption, reduced seal strength, and greater variability, as observed with material C1 at the lowest production speed.

4. The apparently higher melting temperature of material C2 offered a clear example of a steady increase in seal strength with increased heat input at 140 CPM, whereas material C1 showed more consistent performance at lower temperatures. Polymers with higher melting points appear less negatively affected by excessive heat than those with lower melting points, but they also do not benefit significantly from elevated temperatures.
5. The device developed in this study was effective in identifying optimal relationships between seal strength, heat input, and consistency, while proving itself useful for material comparisons — provided that the mechanical properties (particularly bending stiffness and, ideally, friction coefficient) of the materials are similar. Conducting seal strength testing on finished cups instead of laboratory samples also provides more complete information on the performance of materials, while combining both could give further implications on the severity of the stresses caused by the process. This approach can help improve the efficiency of cup manufacturing by enabling heat input optimization and providing a practical, non-disruptive testing method. Additionally, the findings underscore the importance of testing finished products in multi-stage processes, as laboratory conditions often fail to accurately replicate actual production environments. Exploring similar methodology in other packages and products facing analogous production conditions that induce post-joining/converting stage stresses could be beneficial in improving understanding on material behavior.
6. This study provided practical and objective method of evaluating side seals of finished cups under industrially relevant conditions. In addition, the findings clarify the trade-offs between ultrasonic and hot air sealing in a high-speed converting process while advancing general understanding of how to evaluate materials in the paper cup manufacturing process. The presented seal strength testing method is presumed to be applicable to cups produced on any machine as the maximum production speed or differences in machine construction should not affect the fundamental sealed structure of the formed cup.

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APPENDIX

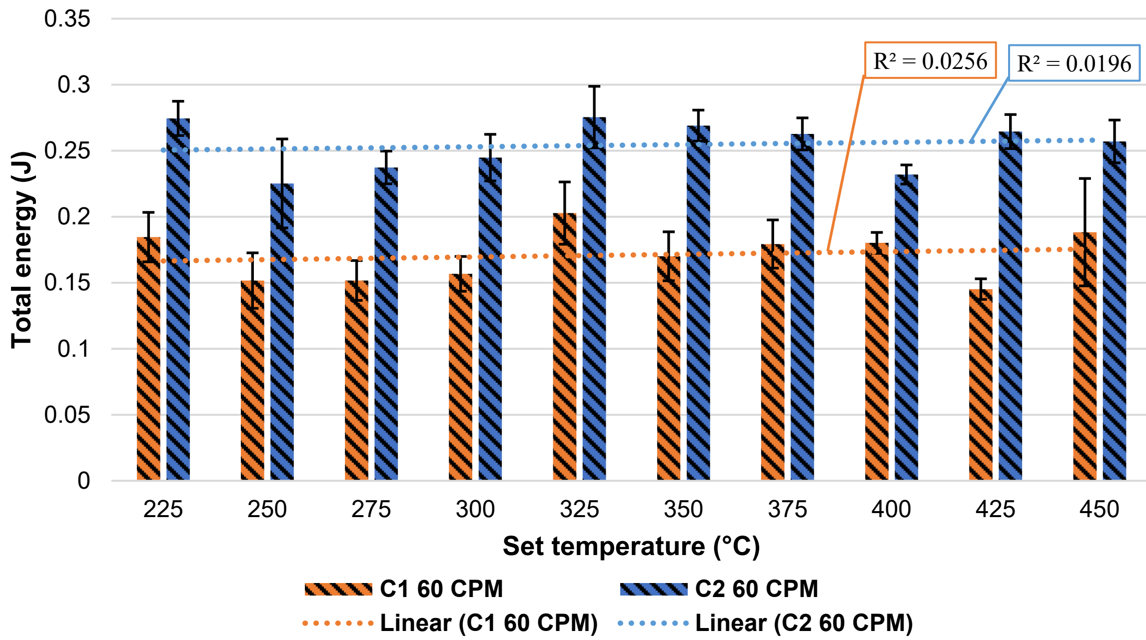

Fig. S1. Seam opening energy for hot air sealing of C1 and C2 at 60 CPM

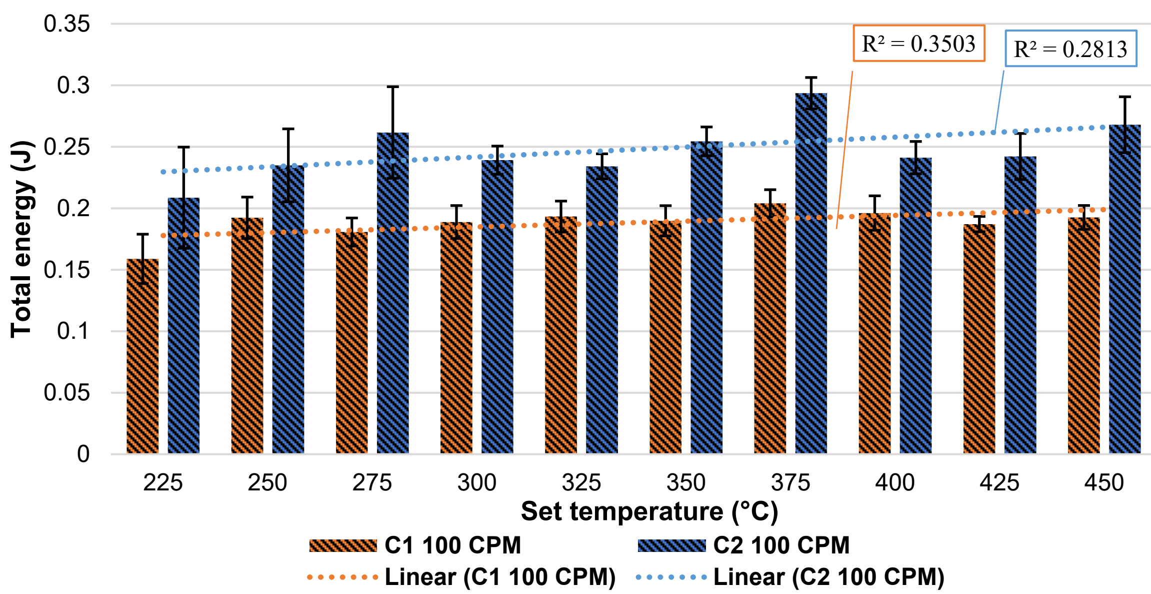

Fig. S2. Seam opening energy for hot air sealing of C1 and C2 at 100 CPM

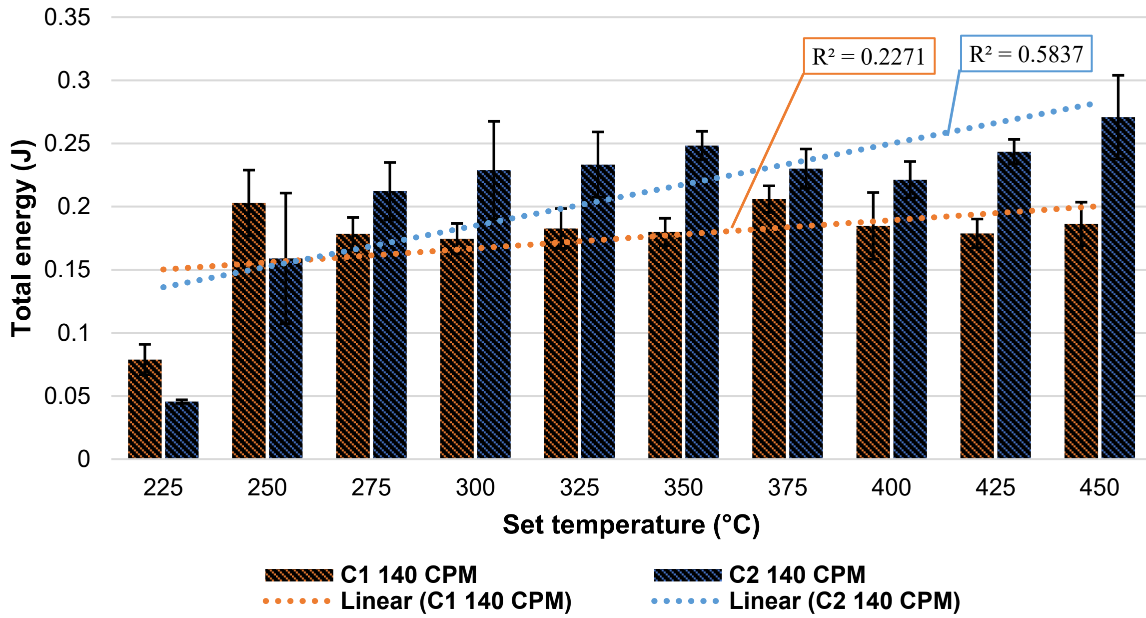

Fig. S3. Seam opening energy for hot air sealing of C1 and C2 at 140 CPM

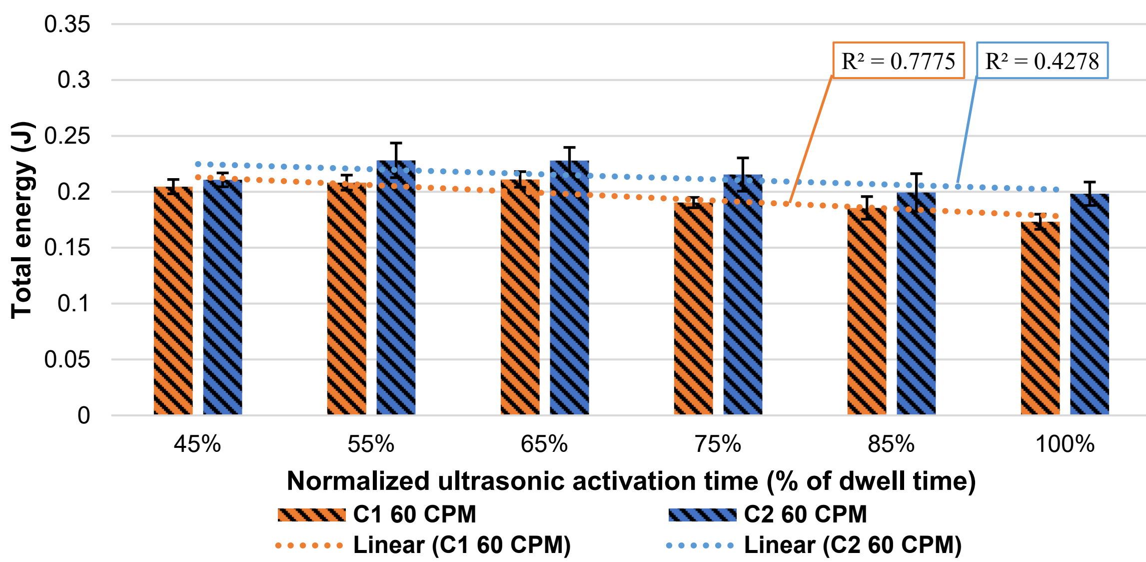

Fig. S4. Seam opening energy for ultrasonic sealing of C1 and C2 at 60 CPM

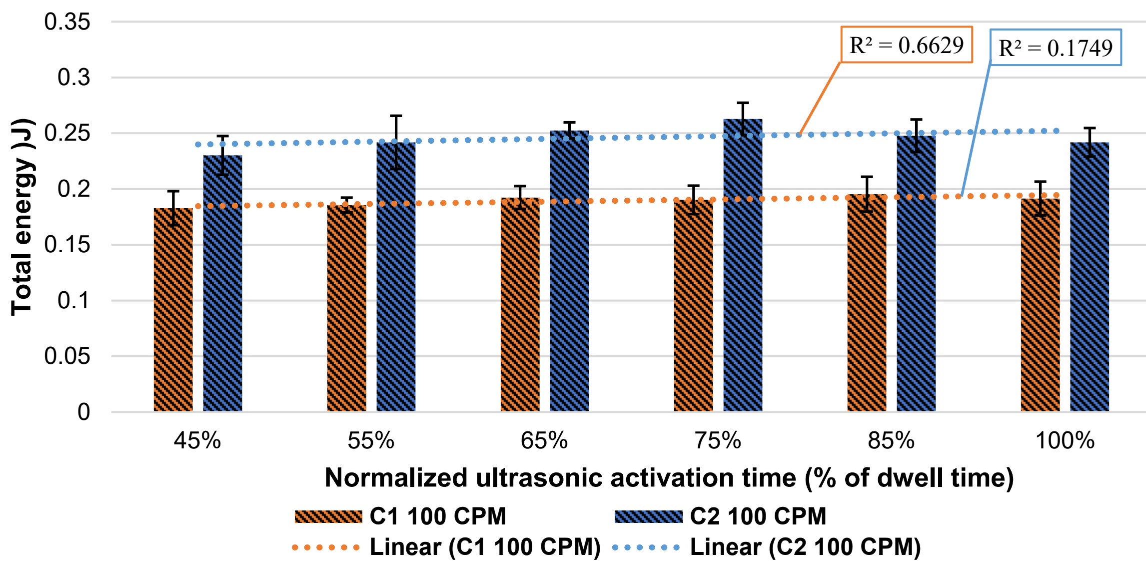

Fig. S5. Seam opening energy for ultrasonic sealing of C1 and C2 at 100 CPM

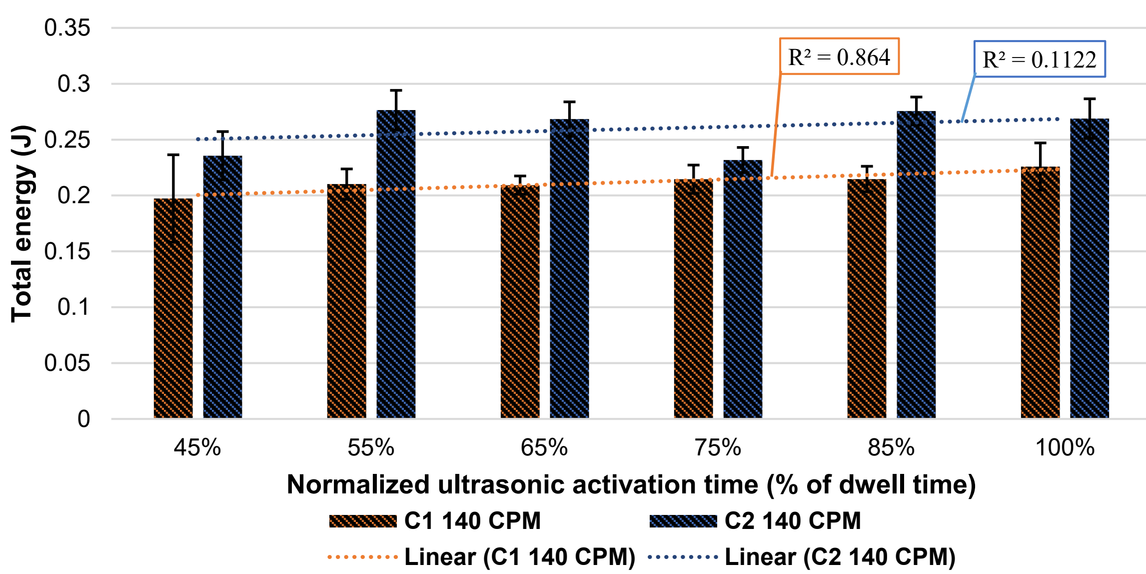

Fig. S6. Seam opening energy for ultrasonic sealing of C1 and C2 at 140 CPM