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Shahid Lakhwani and Katherine W. Hughes
Corning Incorporated

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ABSTRACT

Current trends in automotive emissions control have tended towards reduced mass substrates for improved light-off performance coupled with a reduction in PGM levels. This trend has led to increasingly thinner walls in the substrates and increased open frontal areas, with a potential of reducing the overall mechanical strength of the substrate relative to the thicker walled lower cell density supports.

This change in demand driven technology has also led to developments, at times costly, in the processing of the catalytic converter system. Changes in mat materials, handling technology and coating variables are only a few sources of overall increased system costs.

Corning has introduced the Celcor® XS™ product to the market which significantly increases the strength of thin and ultra thin walled substrates. A thorough evaluation of these products leads us to believe that the new substrate provides significant potential advantages and benefits to the entire supply chain as well as to the OEMs. The current paper will address some of these evaluations and describe some of the benefits associated with the design utilized.

INTRODUCTION

Advantages of thin wall and ultra-thin wall cordierite substrate supports for catalyst coatings have been evaluated in fair detail since their introduction [1-8]. While these substrates provide significant benefits such as low back pressure, faster light-off and increased geometric surface area, one attribute of these aforementioned products that can benefit from an improvement is their overall strength. Simple geometric analysis clearly indicates that, all other properties being constant, a 900/2 (900 cells per square inch and 2 mil wall thickness) product would be weaker, structurally, than a 400/6.5 product of similar dimensions, as shown in Figure 1. The goal of the current work was to utilize some minor structural changes whereby no negative impact on the performance of the substrate would result, while simultaneously significant improvements in the isostatic strength could be gained.

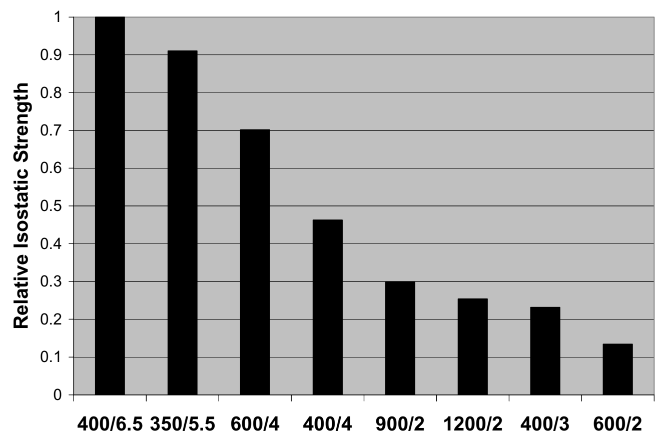

Figure 1. Relative isostatic strength of cordierite substrate supports, as a function of cell density and cell wall thickness

Isostatic strength (Iso) refers to the failure strength of the substrate under isostatic compression. This measurement signifies the load bearing capability of the product, specifically during the canning process. The importance of improving the Iso performance of the product targets benefits that the entire supply chain may potentially take advantage of. The improvements described later in this paper show a potential for benefits through the coating process as well as improvements in terms of a more robust product for the canners.

IMPROVING THE ISOSTATIC STRENGTH

By modifying only the cells close to the periphery of the substrates, a significant improvement in the isostatic strength of the parts was achieved. The goal of the work was to not make any changes to the material itself or to the interior of the substrate. In this fashion, the change could then help provide the benefits of improved strength while maintaining all of the benefits and transparency of the current 900/2 product. The actual changes made were simple geometric modifications, based on optimized designs derived from modeling information. These structural-only changes were evaluated so that other than the isostatic performance, none of the other important attributes of the products were impacted.

Described in this paper are the strength advantages observed with an improved Iso product, henceforth referred to as the Celcor® XS™ substrate, one variation of which is schematically shown in Figure 2. Additionally, a comprehensive evaluation of other key properties essential for the durability and utilization of the substrate in automotive applications is also discussed in some detail.

STRUCTURAL MODELING

Modeling was conducted to determine the best possible designs that would optimize the isostatic strength without any negative implications for thermal shock. Figures 2 and 3 portray some of the assumptions and results of these types of modeling efforts. More detailed versions of these analyses were used to determine the final designs that were adopted for the Celcor© XS™ product.

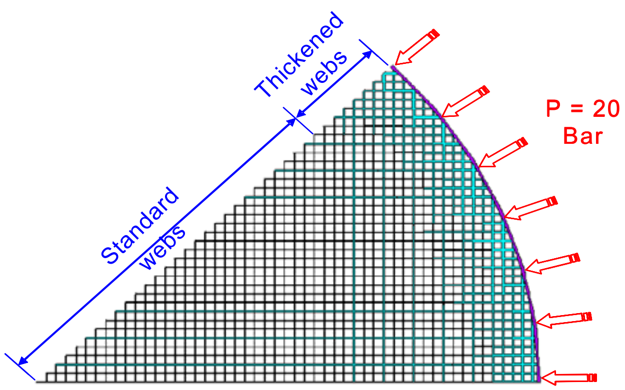

Figure 2. Segment of substrate with assumed applied stress

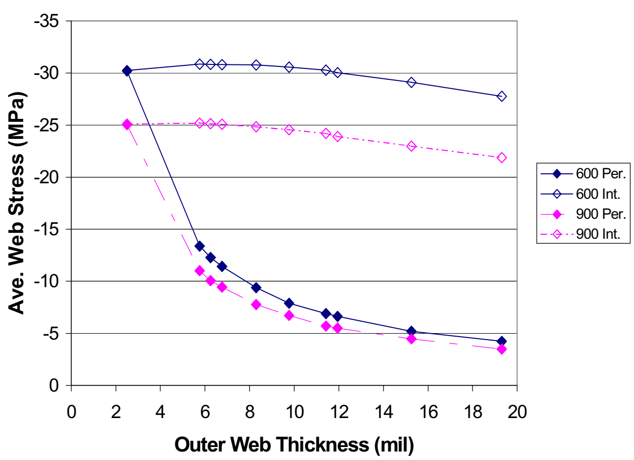

Figure 3. Representative modeling results for 900/2 and 600/2 designs with a specific XS™ feature

Figure 2 indicates the fashion in which the applied stress was modeled on a substrate of a given design and Figure 3 depicts the resulting average stress in the peripheral and bulk webs of 900/2 and 600/2 substrates as a function of the thickness of the outermost/peripheral web. These modeling results also indicate that while the stress change in the peripheral webs can be affected via the design, the bulk of the substrate remains unaffected. Since most Iso related failures typically originate at or near the periphery this would then indicate the preferred design direction to adopt. Hence, based on this type of data coupled with modeling data depicting thermal shock resistance, designs were chosen where an optimized balance of the final physical properties would be expected.

TESTING, RESULTS AND DISCUSSION

The physical properties of 900/2 cordierite substrates of standard design and a particular Celcor® XS™ design were compared via a series of tests. The particular design used for these tests, and the data shown in the remainder of this paper, consisted of a thickening of the outer most cell walls to the point where the balance between the pressure drop, the isostatic strength, the back pressure and the thermal shock resistance of the product was optimized. All of the experimentation was conducted with substrates that were 4.16” in diameter and 4” long. The particular XS™ design chosen for this study, involved the thickening of the peripheral webs, within a range of at least 4 and up to 10 rows of cells adjacent to the outer web. Furthermore, the webs were thickened at a constant rate such that the thickest webs were those that were attached to the skin region. This thickest web ranged from being 2 times to about 4 times the thickness of the standard webs of the substrate [9]. Controlled lots of the standard design and the XS™ design were allocated for this study and all of the data provided hereafter is specific to those lots, unless noted otherwise. While all of the properties listed in Table I were tested, only the properties pertaining to the supply chain usage and end use application will be described here.

Table I. Series of tests conducted for evaluating 900/2 and 900/2 XS Substrates

Strength			CTE	Pressure Drop
MOR	ISO	Shear	Thermal Shock	Simulated Light-off
Image & Phase Analysis			Porosity	Bulk Density
Water Absorption			Peripheral Strength Measurements	

STRENGTH and THERMAL SHOCK

Isostatic strength testing was conducted using a uniform hydraulic pressure around the parts. Parts were placed in a rubber boot and tested to failure detected via “first sound.” In addition to strength testing, the thermal shock resistance of the improved product was evaluated to ascertain that no degradation in the thermal shock properties of the substrate would result as a consequence of the design improvement.

Thermal shock testing was conducted by placing the substrates in a cyclic heating and cooling cycle from room temperature to a peak temperature of 700°C for the first cycle. After completing 20 such cycles the parts were evaluated for any resultant cracks. If no cracking was observed the test was repeated to a peak temperature of 25°C above that of the cycle preceding it. The ramp rates of these cycles were programmed such that the temperature would reach 90% of the peak set temperature within 10 seconds and the actual peak temperature within 20 seconds. Once at peak temperature, the body was maintained there for 90 seconds and then cooled back down in 90 seconds. This methodology was repeated by increasing the peak temperature in increments of 25°C until a detectable failure was observed. Figure 4 summarizes the results from both, the isostatic testing and the thermal shock cyclic testing.

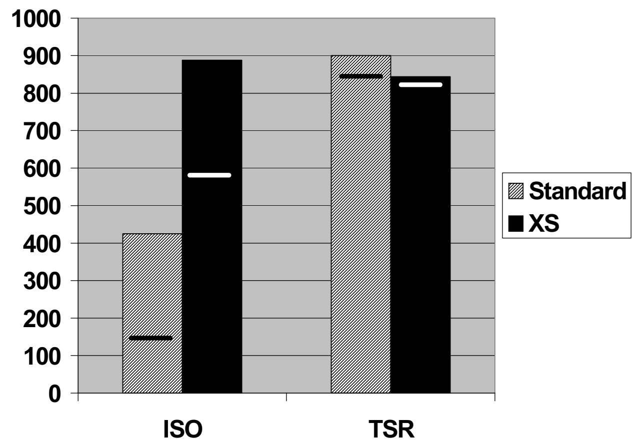

Figure 4. Isostatic strength (ISO) and Thermal Shock Resistance (TSR) data for Standard and Celcor® XS™ 900/2 substrates

The vertical axis of the chart captures both, the strength figures in psi and the thermal shock failure temperatures in (°C). The bar charts for both properties tested are the average values of 18 parts tested for each type of substrate for Iso and 8 parts each for thermal shock. The horizontal lines on the bar charts depict the minimum value of the associated property that was observed for the lots investigated.

Based on the data it becomes evident that introducing the improved feature of the Celcor® XS™ product significantly enhances the strength of an ultra-thin wall body. The average Iso value is improved by a factor of ~ 3, while the minimum value has improved by a factor of ~ 4. Furthermore, both of these values show statistically valid differences. Since many systems are designed around the minimum value of the product attribute, both of these improvements tend to validate the concept of an improved product that should provide potential benefits for the entire supply chain.

As mentioned previously, the thermal shock resistance of the product is also an important variable to consider. When studying the values shown above in Figure 4, the thermal shock resistance of the two products seems to be statistically similar. The minor differences observed in the average and minimum temperatures seen in the figure are individual points and the actual spread of data has substantial overlap for the values of the two products investigated.

TOURNIQUET CANNING

Since the original hypothesis suggested that improved isostatic strength should provide benefits during the canning process, tourniquet canning studies were established to corroborate the results of the aforementioned testing with canning performance. To conduct this examination, a tourniquet apparatus was utilized and uncoated 900/2 parts of standard and Celcor® XS™ designs were evaluated. Since many types of mat materials are available to accommodate the relatively weaker structures such as those produced by a 900/2 geometry, the selection of the mat material was a critical task. In order to determine the benefits of the improved design, an Interam 100 mat, instead of the more expensive and sophisticated hybrid or non-intumescent mats, was selected to assess failure probability under the most aggressive testing conditions. In order to test the parts the study was divided into two sections. For the first, the parts were all canned to a targeted gap bulk density and the resulting losses were recorded. For the second part of the study, all of the pieces, from both designs, were taken to failure and the failure loads were recorded. For both cases, the b-axis of the substrates was aligned to the lap joint of the can, since the lap joint typically produces a point loading.

In the first part of the study where a given and typical gap bulk density for 900/2 substrates was targeted, none of the parts failed. Given that the typical loss percentages during canning are fairly low, this would be an expected consequence of conducting the testing with tens of parts. Therefore the results of the latter part of the experiment became of greater interest. A significant difference was observed in the failure loads between the standard and the XS™ design. A distribution in the frequency of failure at various canning loads (lbs) is graphed in Figure 5.

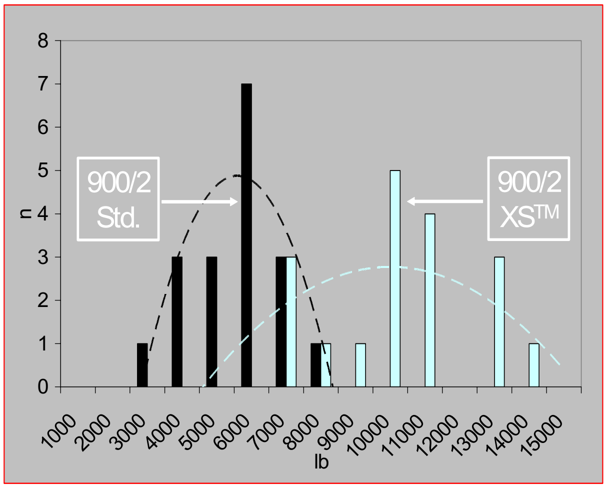

Figure 5. Frequency of failure during canning with associated peak loading

The figure clearly demonstrates that the XS™ design achieves two primary goals. It significantly increases the average load levels needed to fail XS™ substrates relative to its standard counterparts and more importantly it raises the bar for the minimum load needed for failure. While the increased loads needed for failure may not be the most significant find from this study, what becomes important to recognize is the potential improvement this suggests in terms of widening the working range for the gap bulk density. That is, since the XS™ substrates can tolerate higher loads before failing, it stands to reason that a wider range of gap bulk density can also be accommodated with this product relative to the standard 900/2 substrates, therefore providing a wider window of loads and gap bulk densities for the canning process. This would indicate that under the normal course of canning such an advantage should help in further reduction of canning losses.

Encouraged by all of the comparative data described above, further testing was conducted to determine if any of the other important aspects of the product had been affected by the minor changes that resulted as a consequence of the peripheral strengthening. Furthermore, it was also an overall objective of this work that any of the areas that were not specifically targeted should remain unchanged and hence transparent to the supply chain and to the OEMs.

WATER ABSORPTION AND PRESSURE DROP

Since water absorption is one indication of how a substrate performs during the coating process, transparency in this attribute becomes necessary if no modifications to the said process are desired down the supply chain. Water absorption was measured on 8 samples and the resulting data is shown in Figure 6. As noted, and expected, no significant difference can be detected in water absorption. This would imply that the impact of the slight modifications introduced here should be relatively insignificant for the coating process and in general, on the coatability of these parts.

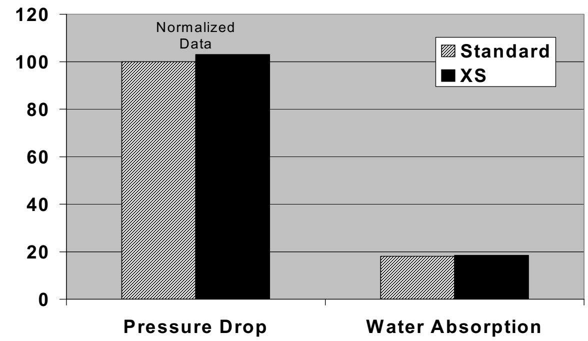

Figure 6. Pressure drop & Water absorption for 900/2 Standard & XS™ substrates

It becomes important to minimize overall pressure drop due to its relationship with engine power output and consequentially fuel economy. Hence the pressure drop of 4.16" round by 4.0" length substrates was measured uncoated using an airflow rig. Standard and Celcor® XS™ substrates were placed in the rig under a sweep of airflow conditions ranging from 10 g/s to 80 g/s, using room temperature air. The resulting pressure drop was thus recorded and is summarized in Figures 6 and 7. The data shown for pressure drop in Figure 6 is the average of all pressure drops over the flow sweep. The primary reason for depicting the data in this fashion is to highlight any observable differences. The full pressure drop curves shown in Figure 7 indicate no discernable difference at all, thereby indicating equivalency and hence transparency on this front as well.

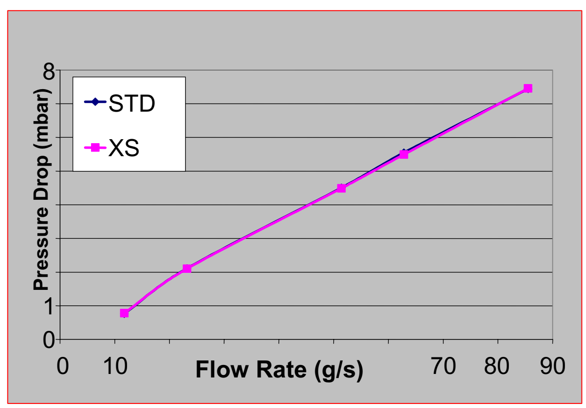

Figure 7. Pressure drop as a function of air flow rate through 900/2 Standard & XS™ substrates

EMISSIONS AND LIGHT-OFF

In addition to the physical property measurements, another attribute that is of great importance is the emissions remediation ability of the overall system. A direct measure of this would entail a coated substrate evaluated either on an engine bench reactor or on an actual engine. A comparison of this sort would allow the observer to determine the transparency between the improved strength product and the standard design. In the absence of coated parts and reactors however, modeling and thermal ramp data were generated to determine potential impacts of the design modification on light-off and steady state emissions conversion.

Modeling

To model the difference between the XS™ substrates and the standard substrates, a one dimensional model was constructed using actual FTP data for the inlet conditions. The inlet data were taken from a previous experiment [10] and reflect the inlet conditions for an FTP test on a ULEV calibrated 2.3L 4-cylinder engine. The conditions for the washcoat and PM loading were set to 107g/l and 58 g/ft^3 respectively, with a bi-metal formulation. The modeling efforts assumed a near flat flow front, so as to mimic the worst case conditions for the given application. Since any change in the strengthened product is only adopted near the periphery, a flat flow front would assume more of the airflow in this peripheral region than would typically result from an automotive exhaust system. Additionally the efforts also focused on the post 30 second period and looked at both 900/2 and 400/4 products in the standard and Celcor® XS™ designs. One of the motivations for including both the 900/2 and the 400/4 data here is to demonstrate the magnitude of the difference between the standard and the XS™ substrates of the same cell density and to then compare that to differences between product families. Figure 8 demonstrates the outcome of this modeling work. The resulting chart shows the standard design as the solid lines for both the cell geometries while data on the Celcor® XS™ are depicted by the dashed line. From this it should be clear to the reader that the difference between the standard and the Celcor® XS™ substrates is negligible. This similarity becomes increasingly evident once the difference in the predicted performance of the 900/2 and the 400/4 products is observed. To corroborate this effort further a thermal ramp study was also conducted.

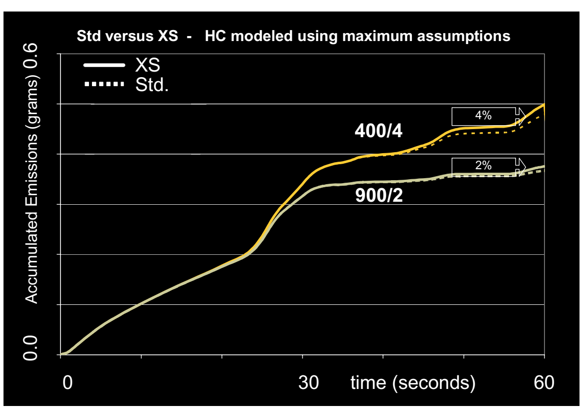

Figure 8. Modeled emissions data for 400/4 & 900/2, comparing standard and Celcor® XS™ designs

Thermal ramp study

The thermal ramp study was also conducted in lieu of having coated parts which could be tested on an engine. Since light-off performance is a key attribute for ultra-thin wall products, one way to investigate any impact that the substrate changes may have had on this performance was to determine the rate at which the current and the improved substrates heated. In the case of the thermal ramp study, both types of 900/2 substrates were placed in a cyclic thermal ramping unit and mapped with 13 thermocouples buried 1 inch deep into the front face of the substrate, fed from the back of the part. Figure 9 schematically indicates the locations of these thermocouples.

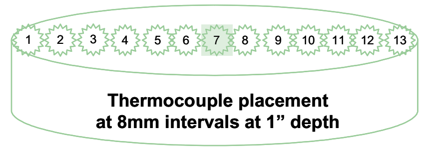

Figure 9. Schematic representation for placement of thermocouples

The burner was ramped from room temperature to 800°C and the temperatures at the thermocouple locations were recorded. While the data currently available from this testing are for 400/4 substrates only, similar trends are expected for all cell families. The data from this testing, shown in Figure 10, indicate that the difference between standard and Celcor® XS™ substrates is minimal and also within the range of error of the test. The one piece of data that suggests a significant difference is for the thermocouples at locations 5 and 9. However, for these particular locations a movement in the thermocouple positions had occurred during the testing, thereby causing the slight inconsistency seen in this particular set of data. In general therefore, it may be stated that these series of tests also suggest transparency between the two designs investigated.

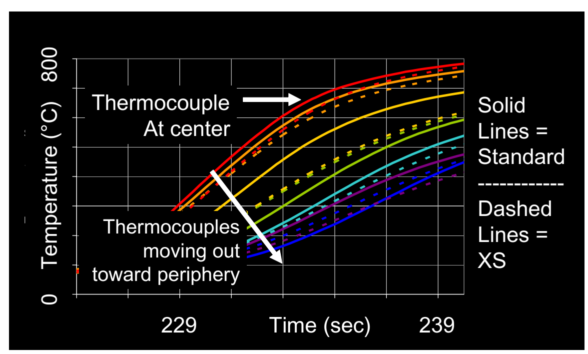

Figure 10. Thermocouple data from thermal ramp study

COATED SUBSTRATE EVALUATION

A series of similar tests were also conducted on Standard and Celcor® XS™ 900/2 parts which were coated by a global coater. As before, all of the parts were 4.16" in diameter and 4" long. The parts were coated in a fashion similar to the one typically used to coat standard 900/2 parts by this global coater during production. Furthermore, the washcoat loading on the standard and XS™ parts used for this study was also kept at the same level as that used for standard 900/2 parts during production. Isostatic strength, pressure drop and thermal shock resistance of these parts was evaluated. Data from this testing are shown in the bar charts in Figure 11. Most interesting is the impact of the coating on the Iso strength of the parts. While it is commonly known [11-14] that coatings aid in increasing the Iso strength of substrates, it is curious to observe the difference in the Iso values of the coated standard and coated XS™ substrates relative to the values shown in Figure 4. The magnitude of the increase in the Iso value for Celcor© XS™ is substantially greater than that of the standard 900/2 product. While a clear explanation for this behavior is currently not known, it may be hypothesized that the coating process, in a sense, magnifies the peripheral feature that differentiates the improved product from its standard counterpart.

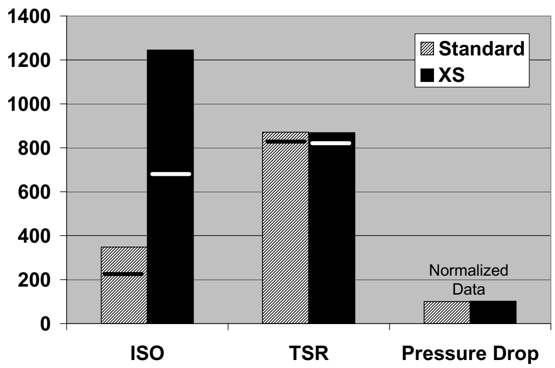

Figure 11. Isostatic performance, thermal shock resistance and pressure drop performance of 900/2 standard and Celcor® XS™ design substrates

Another noteworthy summary of data depicted by Figure 11 is the reduction in the difference of the thermal shock threshold between standard and XS™ substrates, signifying that the effective thermal shock behavior of the two is the same.

Finally, one should also note from the same figure that the pressure drop of the two types of coated substrates show no difference in performance. This indicates that no negative change in the impact on engine performance should be expected by introducing this improved feature to the current 900/2 design.

CONCLUSION

Evolution, not revolution, could be construed as the mantra for the Celcor® XS™ substrates. While significant improvement is observed in the isostatic performance of the product relative to its current 900/2 counterpart, thorough evaluation of other properties of interest show that there is no change in the performance of the XS™ product in other respects. The thermal shock performance, water absorption, pressure drop and light-off all seem to be transparent in nature.

Coating the parts tends to further, and more than expectedly, enhance the performance of the Celcor® XS™ product with respect to isostatic performance, while maintaining transparency in the other aforementioned areas. Coupling the data discussed for the uncoated and the coated substrates it is concluded that the goal of significantly strengthening ultra-thin wall substrate supports has been achieved without causing any adverse impact on other attributes.

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