RETHINKING AREA RATIO: A Physics-Based Model for Predicting Solder Paste Transfer Efficiency for Thin Stencils

by Gayle Towell, AIM Solder Technical Marketing Lead

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Area ratio (AR) has long been the industry standard for predicting solder paste transfer efficiency (TE) and guiding stencil aperture design. However, as electronics manufacturing pushes toward ultrafine pitches and thinner stencils, inconsistencies in TE have emerged despite AR values being above the recommended 0.60 threshold. This study examines the theoretical foundations of stencil paste release, focusing on the interplay between gravitational forces (which scale with paste volume) and adhesive forces between paste, stencil walls, and substrate (which scale with surface area).

Here, an alternative model for variable AR limits that accounts for variations in stencil thickness is proposed. To test this approach, the model was applied to pre-existing experimental data obtained from previously published papers in which print tests with differing stencil thicknesses were used. Findings indicate that a stencil-thickness-dependent AR limit provides a more accurate predictor of TE across varying stencil designs and could inform future industry standards for ultrafine solder paste printing.

Introduction

The area ratio is widely used in surface mount technology (SMT) as a metric to predict solder paste transfer efficiency during stencil printing. Defined as the ratio of the aperture cross-sectional area to the total wall area of the aperture, this value serves as a proxy for whether solder paste will effectively release from the stencil and deposit onto the printed circuit board (PCB).

Industry guidance, such as IPC-7525 [1], generally recommends a minimum area ratio of 0.60 to achieve good print performance. However, as electronic components continue to shrink and stencil thicknesses decrease to accommodate finer pitches, this metric begins to show its limitations. Users frequently observe that the 0.60 threshold does not universally apply, particularly when aperture geometries or stencil materials deviate from conventional norms. These discrepancies suggest that the original formulation of the area ratio rule is rooted in simplifying assumptions that may no longer hold under modern manufacturing conditions.

Area Ratio as a Metric for Print Transfer Efficiency

The area ratio threshold currently in use is based on a force balance model involving two adhesive forces: adhesion between solder paste and stencil walls, and adhesion between solder paste and substrate. The assumption is that paste release occurs successfully when the adhesive force pulling the paste onto the board exceeds the adhesive force holding it inside the aperture. In this model, the adhesive force between the solder and any surface is considered to be proportional to the surface area in contact and the intrinsic adhesion per unit area. This leads to the following condition for successful paste release: $C_1A_1 > C_2A_2$, where:

- C_1 is the adhesion force per unit area between the solder paste and the board
- A_1 is the aperture cross-sectional area
- C_2 is the adhesion force per unit area between the solder paste and the stencil walls
- A_2 is the total stencil wall area in contact with the paste

Rearranging this relationship yields the area ratio inequality:

Area Ratio = $A_1 / A_2 > C_2 / C_1$

Because the constants C_1 and C_2 are difficult to measure directly—each depending on material properties, surface finish, and environmental conditions—the industry-standard threshold of 0.60 has been established empirically.

This ratio provides acceptable results across many common printing scenarios. That said, deviations do occur. For instance, coated stencils—having smoother wall surfaces—can reduce C_2, thereby enabling acceptable release at lower area ratios. Conversely, scenarios involving unusually tacky pastes or rough stencil walls may require higher area ratios for reliable release.

Moreover, this model does not account for all physical factors influencing paste release. A paste's internal cohesion, for example, may be weaker than its adhesion to the stencil, further complicating transfer dynamics. These limitations indicate that while the current area ratio rule serves as a helpful guideline, it is ultimately an oversimplified representation of a more complex physical process.

Limitations of Area Ratio at Reduced Stencil Thickness

It is widely believed that using a thinner stencil improves solder paste transfer efficiency. This perception often stems from scenarios where, in order to maintain the same deposit volume or footprint, reducing stencil thickness necessitates increasing the area ratio, leading to improved release performance in line with the conventional model.

However, when the area ratio is held constant across different stencil thicknesses—meaning the aperture dimensions are proportionally adjusted—many practitioners have observed the opposite effect: thinner stencils tend to yield lower transfer efficiency, not higher. This phenomenon has been reported anecdotally across various production environments, but until now, no published work has provided a theoretical explanation or quantitative model to account for it.

This paper proposes a revised force-based model grounded in fundamental physics principles. The model introduces an additional factor – the influence of gravity on the solder paste deposit – into the conventional release equation and offers a new functional relationship between area ratio and stencil thickness. This approach provides a theoretical basis for the observed decrease in transfer efficiency with thinner stencils and enables estimation of minimum area ratio limits tailored to specific stencil geometries.

Revisiting the Force Model: A New Proposal

To explain the observed decrease in transfer efficiency when stencil thickness is reduced at constant area ratio, it is necessary to revisit the underlying force assumptions. The conventional model considers only two forces in the release process: adhesion between the paste and the stencil walls, and adhesion between the paste and the substrate. However, this simplification overlooks an important third factor—the gravitational force acting on the solder paste volume.

The gravitational force scales with the volume of the paste deposit, while the adhesive force between the paste and the board scales with area. Because area and volume do not scale linearly with each other, this introduces a discrepancy that becomes more pronounced with thinner stencils and smaller deposits. In other words, as the stencil becomes thinner, the mass—and thus the gravitational assistance in paste release—decreases faster than the adhesive force to the board, disrupting the expected release behavior. This mismatch is not accounted for in the traditional area ratio model.

Adhesion vs Friction in the Stencil Wall Interaction

In developing the revised model, it was necessary to examine whether the interaction between the paste and stencil walls should be treated strictly as adhesion or as a form of sliding friction. If friction is the dominant mechanism, the resisting force would be described by: $F = \mu N$, where μ is the coefficient of friction and N is the normal force.

Note that the normal force of the paste with the walls of the stencil depends on pressure, which varies with depth, x, as pressure $= \rho g x$. The total force on the walls due to pressure is found by integrating pressure over the area of the walls. In this case, the wall force becomes:

$F = \int_0^T \mu \rho g P x dx = \mu \rho g P T^2/2$, which can be rewritten as $\mu \rho g A_2 T/2$.

Where:

- ρ is paste density
- g is gravitational acceleration
- P is aperture perimeter
- T is stencil thickness
- A_2 is stencil wall area

However, observational evidence—such as high-speed video analyses by Chrys Shea [2]—suggests that paste release occurs primarily through cohesive stretching and detachment rather than by sliding along the walls. For this model, the stencil wall interaction is therefore treated as a pure adhesion force: $C_2 A_2$, where C_2 is the adhesion force per unit area. In future work, this assumption may be revisited for specific scenarios, such as highly polished or coated stencils, or low-cohesion solder pastes. For now, the model assumes adhesion dominates.

Modified Force Relationship for Paste Release

Incorporating the gravitational force into the original release condition yields a revised force balance: $C_1A_1 + \rho Vg > C_2A_2$

Where:

- C_1 and C_2 are adhesion force per unit area between paste and board and between paste and substrate, respectively
- A_1 and A_2 are the aperture cross-sectional area and the area of the stencil walls, respectively
- ρ is the density of the paste
- V is the volume of the solder deposit
- g is gravitational acceleration

Since $V = A_1T$, where T is stencil thickness, and grouping constants for clarity, let $C_3 = \rho g$, the gravitational force per unit volume. Substituting gives: $C_1A_1 + C_3A_1T > C_2A_2$

Factoring out A_1 gives the following: Area Ratio $= A_1 / A_2 > C_2 / (C_1 + C_3T)$

This expression describes the area ratio limit required for successful paste release as a function of stencil thickness. Importantly, it shows that as T decreases, the denominator shrinks, which increases the required area ratio.

To further simplify the expression, let $a = C_2 / C_3$, and $b = C_1 / C_3$. Then the area ratio limit becomes: Area Ratio Limit $= Y(T) = a / (b + T)$

As an illustrative example of this relationship, assume an area ratio limit of 0.60 is valid for a 5-mil (127 µm) stencil and increases to 0.80 for a 1-mil (25 µm) stencil. These values correspond to a = 9.6 and b = 11. The resulting curve, shown in Figure 1, visualizes how area ratio limits would change with stencil thickness based on these boundary conditions.

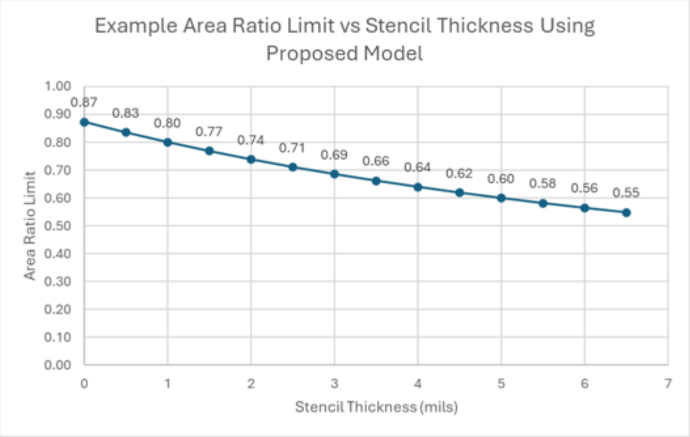

FIGURE 1. How the area ratio limit might vary with stencil thickness per the proposed model.

Validating the Proposed Model with Pre-Existing Data

To evaluate the validity of the proposed area ratio model, several published studies were examined that reported print transfer efficiency across different stencil thicknesses and area ratios. While no studies were found that directly aimed to quantify area ratio limits as a function of stencil thickness, several provided suitable datasets for retrospective analysis.

This data is used to determine whether the area ratio limits required to achieve 75% transfer efficiency increase as stencil thickness decreases, as predicted by the model. For each dataset, transfer efficiency versus area ratio was plotted, derived area ratio cutoffs corresponding to 75% efficiency were determined, and the resulting points were fitted to the proposed function to assess consistency.

Validation Using Data Sets with Three Stencil Thicknesses

The first data set comes from the paper titled, “An Investigation into the Use of Nano-Coated Stencils to Improve Solder Paste Printing with Small Stencil Aperture Area Ratios” [3]. This study reported transfer efficiency results for stencil thicknesses of 3, 4, and 5 mils, across three solder paste types (Type 3, Type 4, and Type 5), and included both uncoated and nano-coated stencil conditions. The original intent of the study was to evaluate the benefits of nano-coatings, however the structure of the data made it well-suited for testing the predictive power of the proposed area ratio model.

The results for uncoated and coated stencils across each paste type and stencil thickness were isolated. For each combination, transfer efficiency was plotted against area ratio. These results are presented in Figure 2.

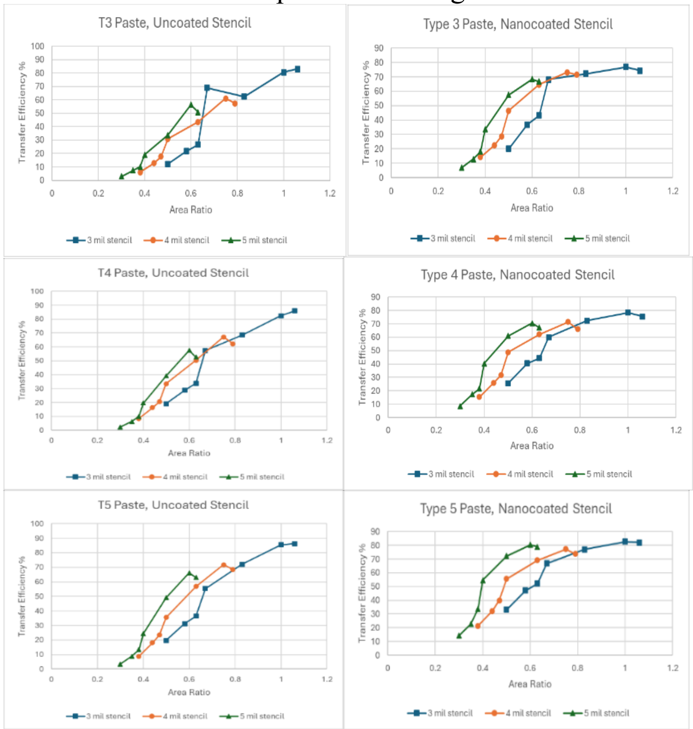

FIGURE 2. Transfer efficiency vs area ratio for uncoated stencils (left) and coated stencils (right).

It is immediately evident from this data that thinner stencils consistently produce lower transfer efficiencies at equivalent area ratios. This trend directly aligns with the predictions of the proposed model.

To ensure consistency and comparability across the dataset, a specific subset of the available data was focused on: print transfer results for 01005 component pads. This aperture type was consistently represented across all paste types, stencil thicknesses, and coating conditions, making it an ideal candidate for model validation.

For each paste type and stencil condition, a linear fit was applied to the corresponding transfer efficiency vs. area ratio plot. From each fitted curve, the area ratio value required to achieve 75% transfer efficiency was interpolated. The derived area ratio cutoffs for all combinations of paste type, stencil thickness, and coating condition are summarized in Table 1.

TABLE 1. Area Ratio Cutoffs from Graph Fits.

Uncoated Stencil						Nanocoated Stencil					
T3		T4		T5		T3		T4		T5	
Stencil Thickness	AR Cutoff	Stencil Thickness	AR Cutoff	Stencil Thickness	AR Cutoff	Stencil Thickness	AR Cutoff	Stencil Thickness	AR Cutoff	Stencil Thickness	AR Cutoff
3	0.953	3	0.906	3	0.878	3	0.930	3	0.919	3	0.822
4	0.875	4	0.810	4	0.766	4	0.753	4	0.783	4	0.714
5	0.707	5	0.692	5	0.636	5	0.625	5	0.618	5	0.546

Note that decreasing the paste size appears to also decrease the area ratio cutoff values across these data sets, with only one exception – type 4 paste printed with a 4 mil nanocoated stencil. The anomaly is likely attributable to uncertainty or error in measurement. This effect could be explored in a future study assessing the impact of paste particle size on this model.

Data points from Table 1 were then used to evaluate the predictive accuracy of the proposed model, defined as: $Y(T) = a / (b + T)$. A non-linear regression analysis was performed for each data series to determine the best-fit parameters a and b, and assessed the quality of each fit using the coefficient of determination (R^2). The resulting fits are illustrated in Figures 3, and the corresponding parameter values and R^2 metrics are summarized in Table 2.

TABLE 2. Fit Parameters.

	Uncoated, T3	Uncoated, T4	Uncoated, T5	Nanocoated, T3	Nanocoated, T4	Nanocoated, T5
a	6.046	6.109	4.848	3.847	4.067	3.627
b	3.246	3.697	2.481	1.132	1.382	1.352
R^2	0.919	0.982	0.983	0.999	0.974	0.946

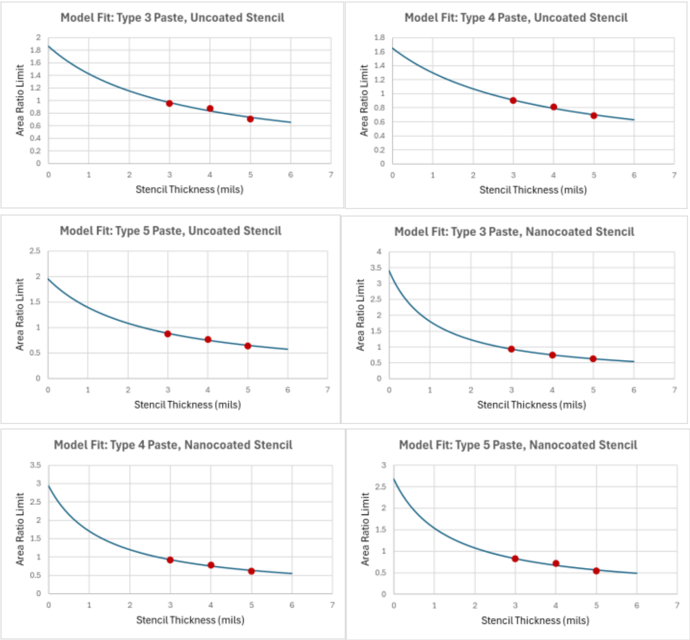

FIGURE 3. Fit of the model to the data for each combination of paste/stencil.

While each fit is constrained by the limited number of data points—reflecting the three stencil thicknesses evaluated—the results demonstrate strong consistency with the proposed model, and the fits are considered reasonable within these bounds.

A second paper was selected to further evaluate the proposed model using a different experimental design. The paper, titled: "The Effect of Area Shape and Area Ratio on Solder Paste Printing Performance" [4], focuses on how aperture shape and area ratio influence print transfer efficiency. Notably, this study includes data for multiple aperture geometries printed across three different stencil thicknesses—80 µm (3.15 mils), 100 µm (3.94 mils), and 120 µm (4.72 mils)—using a single paste type.

For consistency with prior analysis, the data for square-shaped apertures was isolated, which allowed for a direct comparison of print transfer efficiency across stencil thicknesses at identical area ratios. This uniformity eliminates variability due to aperture geometry and makes the dataset particularly well-suited for evaluating whether stencil thickness alone influences transfer efficiency. Figure 4 presents the resulting plot of transfer efficiency versus area ratio across the three stencil thicknesses.

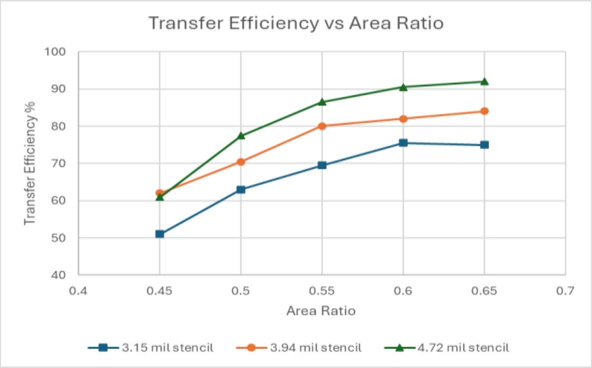

FIGURE 4. Transfer efficiency vs area ratio for data from second paper.

As with the previous dataset, the thinner stencil consistently shows lower transfer efficiency at the same area ratios, reinforcing the model's central prediction that reduced stencil thickness increases the minimum area ratio required for acceptable release. Linear fits to each stencil thickness dataset were applied and the area ratio corresponding to 75% transfer efficiency was interpolated. These cutoff values are summarized in Table 3.

TABLE 3. Area Ratio Cutoffs from Graph Fits.

Stencil Thickness (mils)	Area Ratio Cutoff
3.15	0.62
3.94	0.54
4.72	0.51

Using these data points, the results were again fitted to the proposed model, Y(T) = a / (b + T). The best-fit parameters were a = 4.306, b = 3.853, R^2 = 0.962 and corresponding model curve is shown in Figure 5.

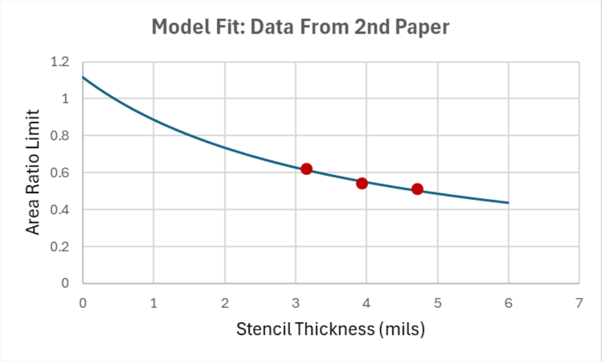

FIGURE 5. Fit of the model to the data from the second paper.

Although limited to three stencil thicknesses, the consistency of this dataset—combined with the observed trend and quality of fit—provides further support for the validity of the proposed model. The strong R^2 value indicates that the functional form captures the stencil thickness effect well, even in the presence of potential confounding factors such as paste variability or leveling effects at higher thicknesses.

Validation Using Data Sets with Two Stencil Thicknesses

To further evaluate the applicability of the proposed model, several additional studies that reported transfer efficiency results for two stencil thicknesses were analyzed. Although these studies provide fewer data points, they offer further insight into whether the relationship between stencil thickness and required area ratio for effective transfer holds under different materials, processes, and printing conditions.

Data was selected from the papers titled "Fundamental Study on a Secure Printing Process Using Nanowork Stencils for 01005 Components" [5] and "Effect of Stencil Technology on Ultra-Fine Pitch Printing" [6]. The first of these papers included transfer efficiency data for 80µm and

100µm stencil thicknesses, evaluated with both Type 4 and Type 5 solder pastes. For consistency, the results associated with rounded rectangular apertures were focused on. The second paper compared multiple stencil types, including laser-cut and electroformed stencils, with and without nano-coatings. Data were collected across 100µm and 120µm stencil thicknesses. Although the data includes a variety of aperture types, multiple scenarios where similar aperture shapes were identified to allow for direct comparison. Graphs of transfer efficiency vs area ratio using data from these papers are found in Figure 6.

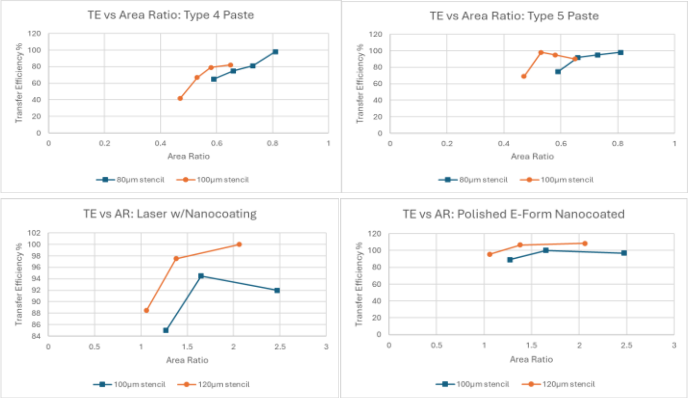

FIGURE 6. TE vs AR from the first paper with 2 stencil thicknesses (top), and the second paper with two stencil thicknesses (bottom).

Though these studies are limited to two stencil thicknesses each, the consistent trend across all datasets supports the core premise of the proposed model. In each case, decreasing stencil thickness leads to a measurable decline in transfer efficiency at constant area ratio—an effect that the conventional area ratio threshold fails to explain, but which is anticipated by the revised physics-based formulation.

Summary of Results and Future Work

The proposed model, which introduces a thickness-dependent term into the traditional area ratio formulation, demonstrates strong alignment with a broad range of pre-existing experimental data. Across multiple studies, stencil thickness was found to significantly influence solder paste transfer efficiency, even when area ratio was held constant—a trend that the standard IPC-7525 guideline does not explain. In contrast, the revised model accurately captures this behavior through a simple, physics-based relationship that incorporates gravitational force and paste volume.

While the current validation is limited to datasets with two or three stencil thicknesses, the consistency of the trend across studies—regardless of paste type, aperture shape, or stencil coating—provides compelling initial support for the model's predictive power.

To further strengthen and refine this model, future work will include a controlled study evaluating print performance across five or more stencil thicknesses, where area ratio, stencil type/coating, and solder paste type are held constant. This will allow for a more rigorous fit of the model and provide greater resolution for evaluating the role of thickness. Additionally, efforts will be made to directly characterize the constants used in the model.

In parallel, additional studies may explore whether sliding friction becomes a relevant force in certain conditions—particularly with smoother or highly polished stencils. High-speed video or force measurement techniques may help identify scenarios where frictional forces dominate over adhesive forces in paste release dynamics.

Conclusions

This work introduces a modified area ratio model that better reflects the physics governing solder paste release during stencil printing. By incorporating the role of gravitational force and stencil thickness, the model provides a robust explanation for a phenomenon that has long been observed but not theoretically justified: the reduction in transfer efficiency with thinner stencils at constant area ratios.

The model offers a practical framework for predicting area ratio limits across varying stencil thicknesses and may help inform future stencil design guidelines and print process standards. While further validation is needed, particularly through controlled experiments and deeper characterization of material constants, the results presented here strongly suggest that the conventional one-size-fits-all area ratio threshold is inadequate in many modern applications.

By advancing our understanding of the mechanics behind solder paste transfer, this model lays the groundwork for improved stencil design strategies, better process control, and ultimately, higher yields in fine-pitch SMT assembly.

Acknowledgements

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