Gains in Metallizing Economics through Improved Evaporator Boat Design

Ramamoorthy Ramasamy, David M. Rusinko, Gregory A. Strosaker and James A. Ricker
GE Advanced Materials - Ceramics, 22557 W. Lunn Rd, Strongsville, OH 44149

Abstract

Historically, vacuum metalizers have faced a tradeoff in boat selections. Three-part boats exhibit better wettability while two-part boats show improved corrosion resistance and life. New technology has been developed which helps overcome this traditional tradeoff, giving a wettable, long-life boat design, and results supporting the improvements will be presented. An analysis of the impact of improved boat design on the economics of operating a metalizing line is discussed.

1. Introduction

Vacuum metallization processes commonly employ resistive type evaporation boats made of inter-metallic composite (IMC) materials comprising boron nitride (BN) and titanium diboride (TiB_2) as the main constituents. Though metallization of aluminum, copper, nickel, zinc, and tin is possible by using these boats, aluminum metallization is the predominant use in the industry. In the metallization process, the evaporator boat is heated to temperatures around 1500 °C by applying an electric current. Metallic wire is continuously fed to the top surface of the evaporator boat, which is at a temperature sufficient enough to melt and evaporate the metal charge. The rate of evaporation and the film uniformity are dependent on the surface area and stability of the puddle on the boat. The metal melt spread over the boat surface acts like a corrosive acid and deteriorates the boat over time.

The important material properties of the metalizing boats are wettability, corrosion resistance to molten metal, electrical resistivity, toughness, and crack resistance. Exposure to humidity before use, consistent vacuum in the metalizer, proper clamping of the boats and controlled break-in power to the boats are some of the external parameters affecting the overall boat performance. Figure 1 shows a schematic diagram connecting the boat properties and the process variables to the overall performance in vacuum metalizing. This paper is intended to discuss the boat properties affecting the metalizing efficiency, a new boat technology for improved performance and a value tool to see the end user benefits of the new technology boat.

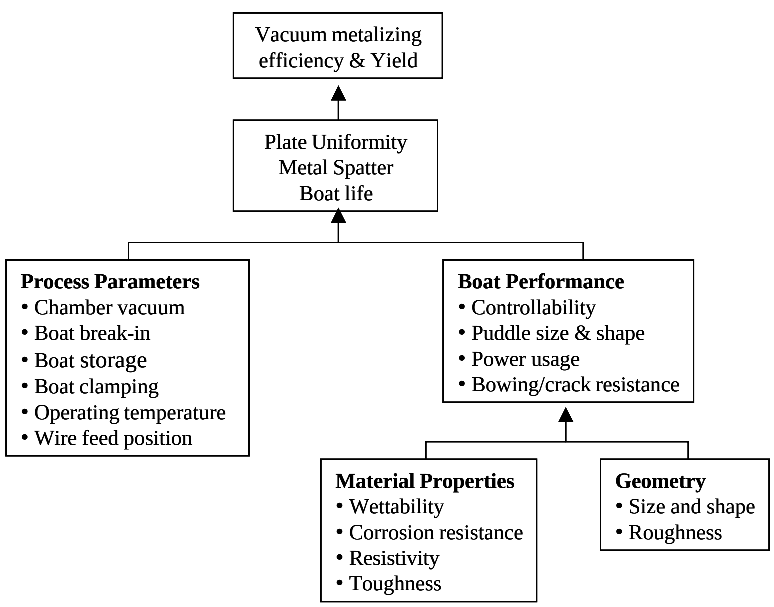


Figure 1. Flow diagram of property-performance relationships in vacuum metallization using IMC boats

Boat wettability and corrosion resistance are typically inversely related, and this creates a tradeoff between evaporation rates and boat life. This has led boat producers to offer two alternative solutions to metallizing needs: two-part boats (BN and TiB_2) that are typically assumed to offer longer life, and three-part boats (BN, TiB_2, and AlN) that are typically assumed to offer better wettability.

1.1. Wettability

The boat's wettability by the molten metal is a critical factor for coating uniformity. More wettable the boat larger is the puddle spread and improved puddle stability allowing high evaporation rates at lower temperatures. Relative surface energy between the molten metal and the boat material is the driver of wettability. The boat surface energy can be manipulated by impurities, composition, surface roughness, chemical reactions, and temperature. Generally it is observed that the three-part boat containing aluminum nitride (AlN) is more wettable for aluminum compared to a two-part boat. IMC boats typically undergo a transition from non-wettable to wettable at temperatures between 1250 – 1400 °C and is generally represented by a contact angle Φ between the boat surface and the tangent line drawn at the point of contact of the melt on the boat as shown in figure 2. A smaller contact angle represents better wettability.

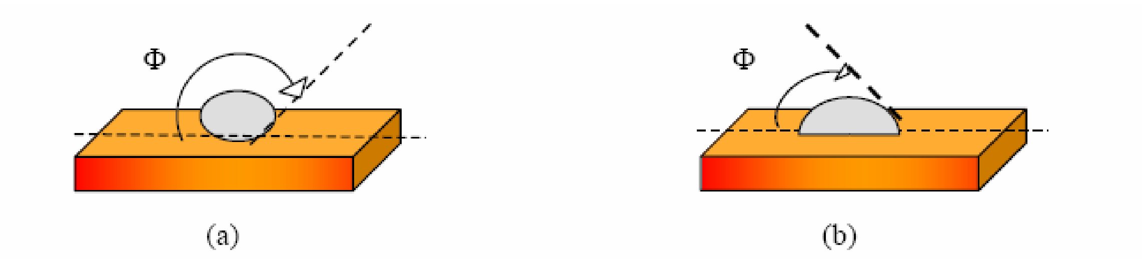


Figure 2. Contact angles representing two cases of boat wettability by molten metal: (a) poor wetting boat and (b) good wetting boat

1.2. Corrosion Resistance

As the molten metal is in continuous contact with the boat surface during operation, the boat experiences corrosion throughout its wet time. Molten aluminum reacts with boron nitride in the boat and forms aluminum nitride and boride compounds. High Wettability it is typically associated with increased degree of corrosive reaction with the boat, which results in deep grooves, leading to reduced useful life. As the grooves deepen, they act like reservoirs for the metal melt and cause spitting and inhibit spreading of the melt resulting lower evaporation rates at a given temperature and premature failure.

1.3. Boat Life

Boat life is an important criterion for achieving high output in film metallization. Increased boat life decreases machine down time and the overall boat costs. The boat life is a function of puddle size and stability over time and degree of groove formation. Material constituents capable of resisting reaction with molten aluminum at high temperatures for a prolonged period of time are a key element determining the operational life of the boat.

1.4. Two-Part Boat vs. Three-Part Boat

A trade-off comparison between the performance criteria of two-part (BN and TiB_2) and three-part (BN, TiB_2, and AlN) boats based on internal measurements is presented in Table 1.

Boat properties	2-part boat	3-part boat
Wettability	-	+
Corrosion resistance	+	-
Boat life	+	-
Coating uniformity	-	+
Puddle size	-	+
Line speed	-	+

Table 1. A trade-off comparison between 2-part and 3-part boat performance.

As it can be noted, two-part boats generally exhibit better corrosion resistance and longer life compared to the three-part boats whereas the later has higher wettability and hence larger puddle size, giving increased line speed and coating uniformity. Typical failure mode in the three part boat is due to wear and in the two part boat it is poor puddle stability and metal spitting. An ideal boat may be a combination of two-part boat's corrosion resistance and the three-part boat's wettability. In such a scenario, the boat will have a co-existence of improved wettability without reducing corrosion resistance so that longer boat life and better coating uniformity can be achieved simultaneously.

2. New Boat Technology

A new boat technology has been developed through optimization of the grain boundary phases that exist between the TiB2 and the BN particles within a 2-part boat. Properties of grain boundary phases in ceramics and metals have significant impact on material properties such as strength, toughness, temperature stability, chemical reactivity, and surface energy. By optimizing the grain boundary phases, the material properties can be significantly manipulated.

Properties of the grain boundary phases are dependant on a number of parameters, some of which include purity of raw materials, chemical composition, homogeneity, and processing methods. The new technology incorporates stringent purity, particle size, and morphology requirements on the TiB2 and BN raw materials, as well as novel processing methods and optimized grain boundary chemistry, which together result in increased wettability to molten aluminum without compromising the high corrosion resistance typical of 2-part boats.

2.1. Improved Wettability

Figure 3 shows the pictures of aluminum melt on a typical boat and the newly developed IMC boat at 1250°C indicating the difference in wettability between the two boats. It is very clear that the wettability-contact angle is much lower in the new boat compared to that of an existing typical boat indicating improved wettability in the new boat.

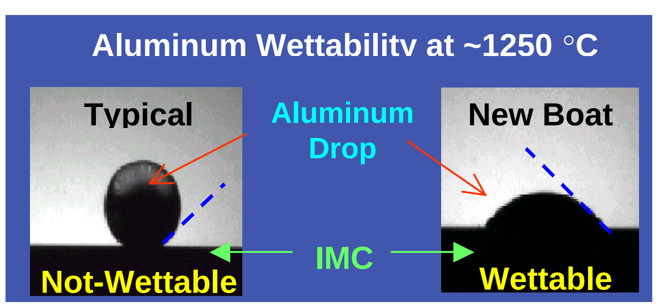


Figure 3. Pictures of aluminum melt at 1250 °C on both a typical boat and the new boat.

The contact angle measurement helps identifying the transition from non-wettable to wettable, but does not directly measures the spreading of the melt as to represent wettability. The area spread of the molten metal over the boat surface is measured at a given temperature. Figure 4 shows a comparative chart of spread area of unit weight of aluminum at around 1400 °C of the new boat to that of the typical 2-part boat.

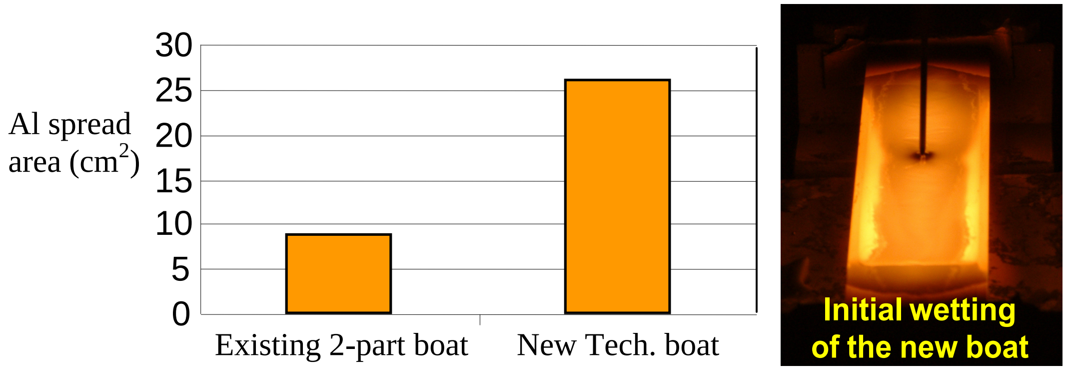


Figure 4. Wettability area chart of the new technology boat and an existing 2-part boat. A picture of initial wetting of the new boat is shown on right side.

From the figures above, it is clear that the new technology boat is >2 times more wettable than the existing 2-part boat.

2.2. Corrosion Resistance

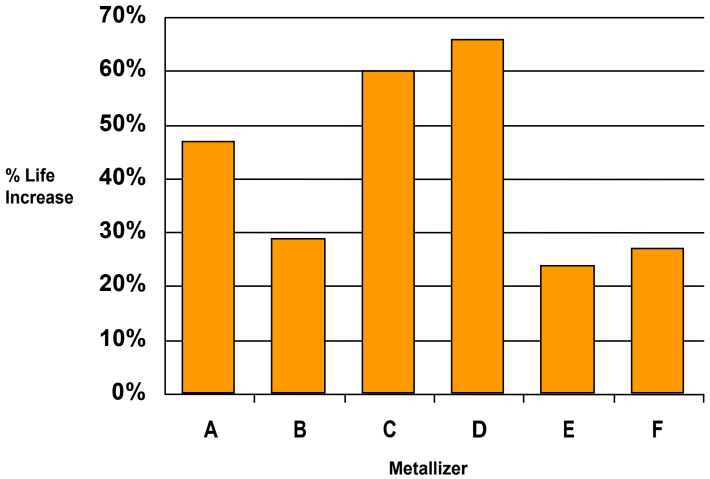
Figure 5 shows the pictures of a typical 2-part boat and the new technology boat after metalizing for 10 hours. It is noteworthy that the groove pattern in the new boat is similar to the typical boat indicating the corrosion resistance is not sacrificed for improved wettability in the new boat. Enhanced chemical resistance of the grain boundary phase and the wettable slag formation around the aluminum puddle suppress the rapid reaction between the aluminum melt and the boat surface.

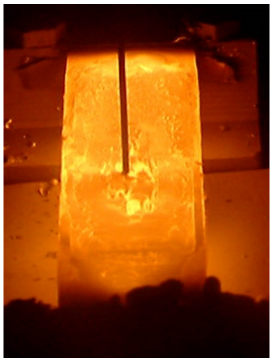
Typical 2-part boat　　New tech. boat

Figure5. Pictures of a typical 2-part boat and the new boat after running for 10 hours. The groove depth In the new boat is comparable with that of the 2-part boat

2.3. Longer Life

In the new technology boat, combination of improved homogeneity and optimized grain boundary chemistry leads to improved wettability while maintaining the corrosion resistance of the 2-part boat leading to a overall longer life. Additionally, the slag formed by the reaction products is wettable to molten aluminum and helps stabilize the metal puddle and contributes to longer operational stability. These improvements lead to significant increase in boat life against 2-part and 3-part boats. Figure 6 shows a chart of increased life of the new boat over typical 2-part boats run in different metallizers. A picture of the boat after more than 10 wet-hours of operation indicating robust long life of the boat is shown on the right. A life increase of 23% - 65% is achieved from the new technology boats over the existing ones.





After 10 hrs: highly stable puddle spreads over entire cavity

Figure 6. Chart demonstrating longer life of the new technology boat over typical boats under different real-life conditions. A stable puddle over the entire cavity helps ensure uniform coating even after 10 wet-hours of the boat (right side picture).

The added advantage of larger puddle size and improved life is that it may simultaneously enable increased line speed and longer boat operation resulting in significantly higher output. Figure 7 shows the increased percentage of linear feet of film coated by using the new boat set under different real-life operating conditions. An average of 35% increased productivity is achieved over typical boat set by using the new technology boat.

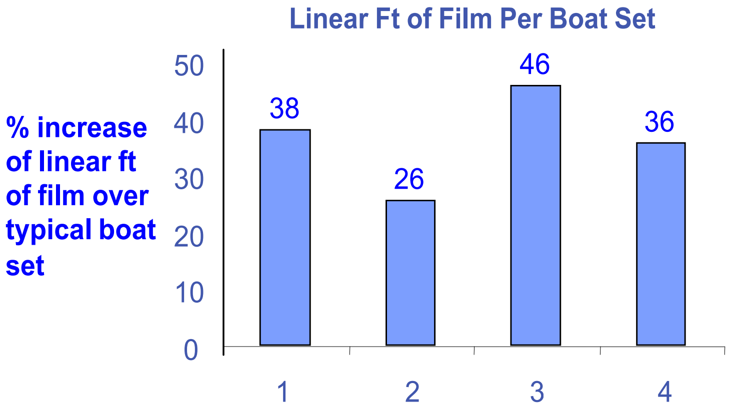


Figure 7. Chart showing increased productivity of film by using the new boat over typical boat set.

3. Value of Improved Boat Performance

Optimization of boat selection and operation can have a significant impact on the profitability of a metallizing operation. Increases in boat life can result in a reduction in operating costs through reduced boat acquisition, disposal, inventory, and transactional costs. Boat life increases can also yield improved operational efficiency and asset utilization by allowing for extra machine uptime due to the reduction in boat changeout requirements. Line speed increases due to improved boat wettability and robustness can also give a measurable improvement in operating efficiency, allowing for higher product output at the same labor and overhead costs.

A modeling tool that helps predict the impact of improved boat performance has been developed. This tool is built around the assumption that the metallizer is capacity constrained on existing shifts and can sell any additional output generated through increased operational efficiency. Furthermore, effective use of the tool requires that the metallizer have good estimates of the "average" values of certain key parameters in their operation, such as roll length, boat life, film revenue and margins, and downtime. While these values must be determined to use the model, the model is designed to allow for a user to experiment with different inputs, so any uncertainty can be tested. The model does not include certain "intangibles" such as transactional, disposal, or inventory costs for boats and the increase in gross margins attributable to increased output with fixed labor and overhead, so the benefits will be even greater than predicted by this tool.

To demonstrate the use of this tool in evaluating the value of improved boat performance, two scenarios have been created. The base case includes the following assumptions:

- Film is OPP in 100,000-foot rolls, with an ASP (for metallized film) of $2.00/lb. and a gross margin of 40%.
- 30 boats (with an acquisition price of $20 each) are used in a set, and they last for an average of 6 rolls, with a line speed of 2000 ft/min.
- Downtime for a roll change (without boat replacement) is 60 minutes, boat replacement adds an extra 60 minutes.

The first scenario (fig.8) analyzes the impact of an increase in boat life by 30%, with a corresponding 15% increase in boat price. Clearly, this will yield direct savings in boat costs through reduced boat quantities. However, the impact from reduced boat changeout time is a more significant driver of profit increase, due to the ability to generate greater sales and therefore gross margins.

Customized IMC Boat Performance Value Calculator

Units	English	Time Basis	Month

Production Schedule	
Shifts	3
Hours / Shift	8
Days / Week	7
Equipment Availability (up-time)	90%

Process Data	
Roll Size (ft)	100,000
# Rolls / Boat Set	6
# Boats / Roll	30
Line Speed (ft/min)	2000

Between-Roll Down Time (minutes)			
Non Boat Change	Venting	10	60 min
	Roll Change & Boat PM	40	
	Pump Down	10	
Boat Change	Venting	10	120 min
	Roll Change & Boat Change	85	
	Pump Down	10	
	Boat Conditioning	15	

Product	OPP
Film Type	OPP
Film Gage (mils)	48
Film Width (in)	80
Film Selling Price / Pound	$2.00
Gross Margin	40%

Boat Performance	Baseline	Actual
% Increased Boat Life	0%	30%
% Increased Line Speed	0%	0%
# Rolls / Boat Set	6.0	7.8
Total Length Film / Boat Set (ft)	600,000	780,000
Total Wet Time / Boat Set (hrs)	5.0	6.5

Boat Costs	Baseline	Proposed	Difference
Boat Price	$20.00	$23.00	15%
Boat Cost / Month	$32,850.00	$29,629.41	**$3,221**

Productivity Improvement	Baseline	Actual	Difference
# Boats Used / Month	1643	1288	-354
# Boat Changes / Month	55	43	-11.8
Additional Up-Time (hrs/ Month)	0.0	12.6	12.6
# Rolls of Film / Month	328.5	334.9	6.4
Film Revenue / Month	$984,389	$1,003,691	$19,302
Film Gross Margin / Month	$393,756	$401,476	**$7,721**

Gross Margin / Month	**$10,941**
Increase	**3%**

Figure 8. Results of a boat life increase on metallizer financials, showing a notable 3% increase in gross margins despite higher boat prices.

The second scenario (fig.9) analyzes the impact of a 10% increase in line speed with a constant boat life (in terms of metallized film length / boat set), again assuming a 15% increase in boat price. In this scenario, the metallizer will pay more for boats (both due to the higher price and increased consumption), but this increase is more than offset by the value of the increased film output. Again, the impact of increased margins due to higher output at fixed labor costs is not included, so the boost to profitability is certainly higher than predicted by this model.

Customized IMC Boat Performance Value Calculator

Units	English	Time Basis	Month

Production Schedule	
Shifts	3
Hours / Shift	8
Days / Week	7
Equipment Availability (up-time)	90%

Process Data	
Roll Size (ft)	100,000
# Rolls / Boat Set	6
# Boats / Roll	30
Line Speed (ft/min)	2000

Between-Roll Down Time (minutes)			
Non Boat Change	Venting	10	60 min
	Roll Change & Boat PM	40	
	Pump Down	10	
Boat Change	Venting	10	120 min
	Roll Change & Boat Change	85	
	Pump Down	10	
	Boat Conditioning	15	

Product	
Film Type	OPP
Film Gage (mils)	48
Film Width (in)	80
Film Selling Price / Pound	$2.00
Margin	40%

Boat Performance	Baseline	Actual
% Increased Boat Life (in film length	0%	0%
% Increased Line Speed	0%	10%
# Rolls / Boat Set	6.0	6.0
Total Length Film / Boat Set (ft)	600,000	600,000
Total Wet Time / Boat Set (hrs)	5.0	4.5

Boat Costs	Baseline	Proposed	Difference
Boat Price	$20.00	$23.00	15%
Boat Cost / Month	$32,850.00	$39,264.80	**$6,415**

Productivity Improvement	Baseline	Actual	Difference
# Boats Used / Month	1643	1707	65
# Boat Changes / Month	55	57	2.2
Additional Up-Time (hrs/ Month)	0.0	24.9	24.9
# Rolls of Film / Month	328.5	341.4	12.9
Film Revenue / Month	$984,389	$1,023,144	$38,755
Film Gross Margin / Month	$393,756	$409,258	**$15,502**

Gross Margin / Month	**$9,087**
Increase	**2%**

Figure 9. Results of a line speed increase (at constant boat life) on metallizer financials, showing a notable 2% increase in gross margins despite higher boat quantities and prices.

4. Conclusions

Improvements in boat technology are helping to break the traditional dilemma a metallizer faces in choosing between the stability of 3-part boats and the life of 2-part boats. This technology employs unique binder chemistry at the grain boundaries of the composite to increase boat wettability of a 2-part boat while maintaining its high corrosion resistance. The result is longer boat life. The impact of improved boat performance on metallizing economics goes well beyond the potential to use less boats due to a life increase, as the additional output possible from reduced downtime or higher line speeds provides significant benefits.