ADVANCES IN HIGH PERFORMANCE ENAMELS

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Advances in High Performance Enamels

Charles Baldwin[1]

[1] Ferro Corporation, 4150 E. 56th Street, Cleveland, OH 44105 USA

Introduction

A modern kitchen with a pans and a range provides a good overview of recent improvements in porcelain enamels. The key attributes of environmental-friendliness, mechanical toughness, thermal resistance, cost effectiveness, and efficiency keep enamels competitive with other materials and lead to the creation of new applications and technologies.

Aluminum and Aluminized Steel Cookware

With good scratch and heat resistance, aluminum enamels are widely used on the exterior of pots and pans. These are based on frits with a relatively low glass temperature and high thermal expansion that is compatible with the approximately 590°C (1100°F) melting point and 24×10^{-6}/K linear expansion of aluminum alloys.

The original low-temperature frits contained about 25-40% lead oxide as flux. Recent increases in environmental and regulatory scrutiny such as the European Union Restriction of Hazardous Substances (RoHS) Directive are making the use of toxic substances even in an indirect food contact environment unacceptable.

The solution to the lead content was to replace it with about 8-12% vanadium pentoxide as a flux, but this material also has toxicity issues. Due to volatility in commodities prices, the vanadium pentoxide has been reduced to 1% or less. Cadmium-free red colors as well as metallics[1] have also been developed for cookware to catch the consumer's eye on the shelf. An example of a lead-free, low-vanadium, cadmium-free cookware set is shown in Fig. 1 A further improvement in low-temperature enamels has been the development of an easy-to-clean glass/non-stick composite with superior scratch and heat resistance compared to traditional organic non-stick coatings.[2]

Fig. 1 RoHS-compliant red coating on cookware exterior[3]

Another option for a single coat colored enamel is to apply it over enameling grade aluminized steel, which is used to make hollowware and architectural panels. This substrate is decarburized steel coated with 25-40 μm (1-1.6 mils) of a 90% aluminum and 10% silicon alloy. It can be drawn and welded, and the only required surface preparation is an alkaline degrease. Furthermore, a vanadium-free, RoHS-compliant clear frit can be used to make colors and metallics. The expansion curve obtained with an Orton Model 1000R dilatometer in Fig.2 shows how this specially formulated glass fits aluminized steel without containing lead; note, vanadium-based frits have too high of an expansion for aluminized steel.

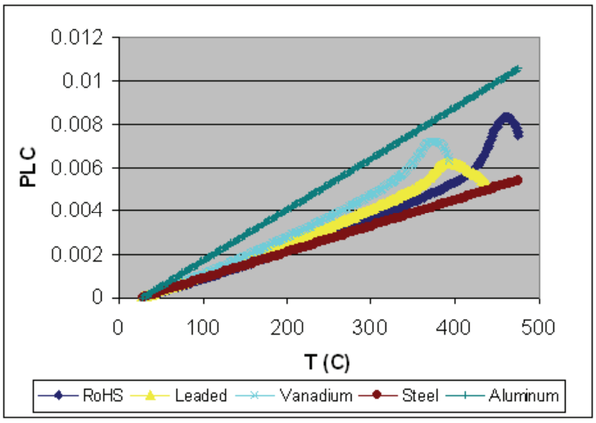

Fig. 2 Thermal expansion of low-temperature frits

Pan Supports

Cast iron is associated with high quality because of the heat capacity, thickness, and weight of the metal. Electrophoresis is a water-based, nearly 100% efficient means of enameling complex cast iron parts with excellent coverage.[4] The ware is the anode in an electrochemical cell, and application of DC current negative charges the porcelain particles. Finally, electro-osmotic dewatering results in a bisque strong enough for part transfer to the furnace. Smooth, acid-resistant matte black enamels have been developed as well as durable single-coat gray and taupe colors. Other types of pan supports currently produced are steel wire pan supports of various dimensions coated with wet spray or electrostatic powder application.

The ferrous pan supports have an uneven heat distribution. An alternative is using cast aluminum as a substrate to take advantage of the thermal conductivity of 140-150 W/m·K and density of 2.71 g/cm^3 compared to 46 W/m·K and density of 7.15 g/cm^3 for cast iron. The thermal image of an enameled aluminum pan support in Fig.3 shows the even temperature distribution from the better distribution of heat energy. Aluminum pan supports offer new market opportunities pleasing to consumers such as a lighter weight stove.[5]

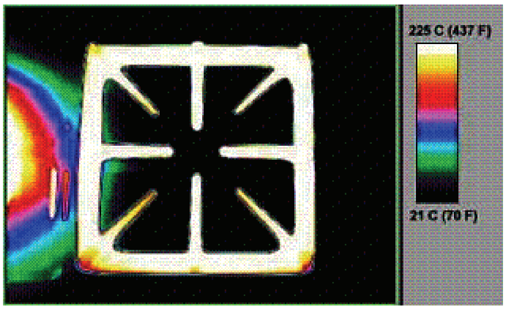

Fig. 3 Thermal image of an enameled cast aluminum pan support

Steel Enamels

Steel is an inexpensive material from which to produce major appliances such as ranges, built-in ovens, and cooktops requiring superior mechanical and thermal performance. “No nickel-no pickle” ground coats permit enameling with a minimal alkaline degrease pretreatment. The wash solution contains hydroxide solutions with surfactants to remove drawing compounds from the metal surface. A typical cleaning cycle for decarburized enameling-grade sheet steel is shown in Table 1 where ambient is room temperature.

Table 1 Typical cleaning cycle for sheet steel

Stage	Time (sec)	Temp (°C)
Pre-Wash	30	Ambient to 50
Clean	60	45 to 70
Clean	60	45 to 70
Rinse	30	55
Rinse	30	Ambient
De-ionized	30	Ambient
Dry		

Steel is typically enameled in mass production with wet spray, wet dipping, or dry electrostatic spray. A high speed flow coater is an alternative to a dip tank, particularly for oven cavities. It reduces manpower and allows two-sided 100% coverage while meeting surface quality requirements with a relatively small footprint. In one published case study[6], a high speed flow coater held 662 L (175 gal) of enamel that was pumped at 190 L/min (50 gal/min) to prevent shear. It was determined that larger flowcoat wands better delivered material than a higher number of smaller nozzles. Overall, the machine operated at 95% first run yield at 13.4 m/min (44 ft/min).

With electrostatically sprayed enamels, the system is 99% efficient because of the use of recycled material. Single fire colors are possible through 2c1f application of base coats or smelted-in color. This is frequently used for coating cooktops.

Powder porcelain is more economical compared to alternative materials such as organic powder paint and stainless steel, particularly because of the resulting long-term durability. Table 2 shows the economics of low- and high-end powder paint versus those of powder porcelain in Table 3. The data is drawn from a published case study[7], and the costs for steel and the coatings have been updated.

Table 2 Powder paint economics

Type	Low Heat Resistance	High Heat Resistance
Line Speed (m/min)	7.6	
Steel (USD/m^2)	15	15
Pretreatment	Alkaline Degrease + Phosphate	
Pretreatment Cost (USD/m^2)	0.022	0.022
Application (mm)	50	50
Potential Pass Yield	98	98
Cost/Area (USD/m^2)	1.05	3.49
Labor (USD/m^2)	0.65	0.65
Hanger Cleaning (USD/m^2)	0.043	0.06456
Scrap (USD/m^2)	0.011	0.02152
Energy Cost (USD/m^2)	0.136	0.142
Total Cost (USD/m^2)	**16.91**	**19.39**

Table 3 shows continuous improvements being made to powder porcelain through the implementation of changes like no-transfer lines to reduce labor and increase quality. While there is a 0.54 USD/m^2 premium for powder porcelain on a more efficient no-transfer line versus a low-heat resistant powder paint, the porcelain offers the advantages shown in Table 4 such as a harder, more heat-resistant coating that requires a simpler, more environmentally-friendly pretreatment. When compared to heat-resistant powder paint, the powder porcelain is less expensive as well.

Table 3 Powder porcelain economics

Type	Transfer	No-Transfer
Line Speed (m/min)	5.5	
Steel (USD/m^2)	15	15
Pretreatment	Alkaline Degrease	
Pretreatment Cost (USD/m^2)	0.005	0.005
Application (mm)	100	100
Potential Pass Yield	92	96
Cost/Area (USD/m^2)	1.53	1.53
Labor (USD/m^2)	0.807	0.65
Hanger Cleaning (USD/m^2)	0	0.075
Scrap (USD/m^2)	0.04304	0.022
Energy Cost (USD/m^2)	0.185	0.167
Total Cost (USD/m^2)	**17.57**	**17.45**

Table 4 clearly shows the value proposition gained by the premium for powder porcelain and certainly maintained against high-temperature paints. Powder porcelain is even more competitive with 304-series stainless steel, which is estimated to cost 38.74 USD/m^2. While stainless steel is a popular appliance finish, it is not only expensive but has high reject rates and poor cleanability and heat resistance.[8] A recent development has been to create metallic colored enamels with the performance of porcelain and an appearance suggesting stainless steel or copper.

Table 4 Powder porcelain value proposition

Process	Powder Paint	Powder Porcelain
Adhesion	Good	Very Good
Corrosion	500 Hrs Salt Spray	Superior
Pencil Hardness (ASTM D 3363-00)	4H	> 9H
Heat Resistance	<< 1000 F	1000+F
Gloss	Less Gloss	High Gloss
Design Restrictions	Less	Some
Process Controls	Pretreatment needs more control	Similar to paint; more guns
Environmental Concerns	Pretreatment	Moderate to None

The quality of powder porcelain has improved over time. Fig. 3 shows data for the percentage of acceptable parts coated for a North American appliance manufacturer from November 2004 to August 2007. A linear fit to the data shows a steady upward increase, and the graph shows fewer significant negative excursions. As light spray and black specks are given as two of the major causes of rejects, it can be concluded the supplier has improved the powder quality through process optimization.

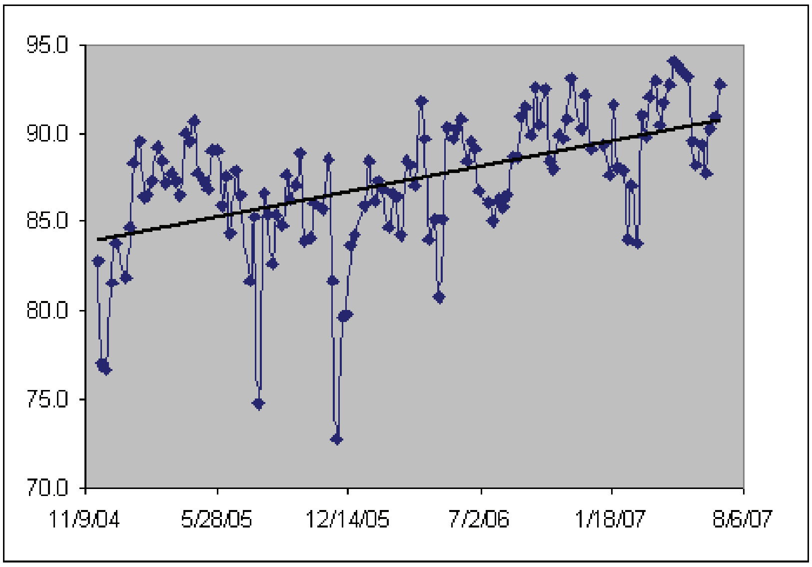

Fig. 3 First pass acceptance on powder porcelain on range parts

It is straightforward to treat the wastewater, dust, and furnace gases from the application of porcelain enamels, and the technology has been available since at least the 1960s.[9] Degreasing and enamel wastewaters need to be neutralized and treated to remove any regulated contaminants before discharging out of the plant or sending to a landfill. With wet enamels, it is possible to use reclaim with a filter press, mix it with virgin material, and coat more pieces. Dust and furnace gases are removed with dust collectors and/or wet scrubbers. In a wet scrubber, pollution gases are brought into contact with scrubbing liquid to remove the pollutants. The pollutants are either sprayed with the liquid or forced through it. These can be designed to collect particulate matter and/or gaseous pollutants, and a mist eliminator separates droplets in the inlet stream from the outlet gases.

Summary

Despite being a mature technology, continuous progress is being made on porcelain enamels. RoHS-compliant single coat colors are available for aluminum and aluminized steel. New uses are being found for low-temperature enamels such as coating cast aluminum pan supports. Also in pan supports, electrophoretic enameling has been developed to obtain excellent coverage and surface colors as matte blacks and single-coat colors are also being used. For sheet steel, ground coats requiring only alkaline degreasing offer an economical, environmentally friendly metal pretreatment. The steel can then be coated in mass in a very cost competitive manner with high speed flow coaters for wet enamels or no-transfer electrostatic powder porcelain lines. Overall, porcelain enamel continues to be economical, durable, and environmentally-friendly.

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