TRANSFER EFFICIENCY: DECISIVE FACTOR IN THE APPLICATION OF ELECTROSTATIC POWDERS

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Transfer Efficiency: Decisive factor in the application of electrostatic powders

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The Transfer Efficiency is an essential requirement of an electrostatic powder, is an index for the quantity of product that settles on the piece in the unity of time.

This quantity can be connected to three different aspects of enamelling:

- On flat ware, the Transfer Efficiency can be connected to the optimization of the enamelling thickness.
- On hollow parts, the Transfer Efficiency is essential for overcoming “Faraday’s cage” and applying all over the piece with uniformity.
- For boilers, a good Transfer Efficiency means applying an uniform thickness both on the upper cap and the lower one.

By this work we develop above mentioned subjects with analytic method and through laboratories tests, in order to explain how a particular development of enamels could make the industrial application efficient.

Introduction and historical outline

The industrialization of porcelain enamels in powder dates back to 1975 in France and since then its diffusion spreads in all directions till becoming the most favourite application system. In a few words we are describing, even if well-known by everybody, the process which is at the root of enamelling process. The electrostatic powder falls onto the piece and settles on it; this simple action could be explained by many physical laws like Gauss’s laws, Coulomb’s theorem, Faraday’s law and “Point” effect. We are investigating those ones that make a more instant impact in the application of an electrostatic enamel. Faraday was the first to discover the electrostatic charges spread on the exterior surface in hollow bodies and therefore the electric field inside these bodies is null and all points of the conductor have the same electrostatic potential. Besides, as our system is dynamic, possible movements of the charges inside the hollow do not modify the charges distribution above the external surface of the conductor and vice versa. All these principles are known as Faraday’s cage.

On the contrary the “Point” effect states that electric charges tend to concentrate on points, a slightly elaborated demonstration follows this simple statement, by which we state that the difference of electric field produces an anomalous deposition in the presence of a strongly curved charged conductor, by using the following formula:

$$E(z) = E(z_0)\exp\left\{\int_z^{z_0} dz\left(\frac{1}{r_1}+\frac{1}{r_2}\right)\right\} \tag{1.1}$$

We apply this connection to a charged conductor, strongly curved on one side of its surface, like for example the one showed in here-under figure.

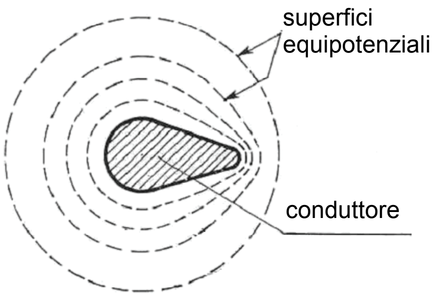


Fig. 1

First of all we must observe (Fig.1) that at adequately large distances from the conductor, the latter can be basically considered dot-like, so that the equipotential surfaces are like spheres with their centre inside (or near to) the conductor. Now we can compare the intensity of the field in the points close to the point side of the conductor with the intensity in the neighbourhood of the other parts of the surface, where there is a smaller bending. If $E_{(Z0)}$ is the modulus of the intensity in electric field on one of the equipotential far (and spherical), E values over the Z abscissa points which are over/on a given strenght line data differ from $E_{(Z0)}$ for the exponential factor which is in the above mentioned formula. As the 1/r curvature has got greater values near to the point, $E_{(Z)}$ is bigger in this area and therefore the charges flux is directed to this area.

During the application of the powder the electrostatic (spray-) gun create an electric field between the gun and the piece to be enamelled; this electric field can ionize the oxygen of the air, that binds itself to the enamel particles which comes into contact, giving a negative charge to it.

By this way a flux of negative charged enamel impacts the piece to be enamelled that has a greater positive potential than the powder. The piece is earthed for continuously discharging such charge. As a consequence of above mentioned laws, the enamel easely builds up in the areas where some “points” are present, like the edges, while it goes off from the hollows, like special pieces with deep pressing (lack of charges). The enamel settles on the piece, loses its charge and permits to the next coatings to settle. Nevertheless, by increasing the thickness of settled enamel, we run into difficulties in dispersing the charge, with a consequent increase in the negative charge of the surface. Such a process goes on till the appearance of “back emissions” (Retroionization); from that time onwards there is no enamel accumulation. This fact must appear at requested thickness, or with bigger thicknesses, so that it does not interfere with enamelling process.

The powder settled on the piece, by time, loses its charge; we try to better understand the reasons for this fact. The system powder-metal sheet can be compared to a plain condenser, where first layers of powder do service as polar dielectric while the following ones behave like the second part of the condenser.

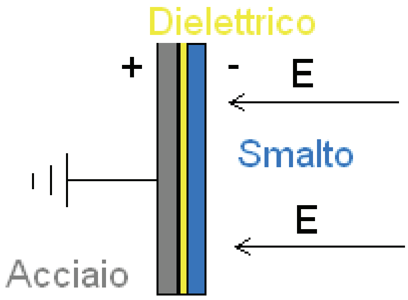


Fig. 2

The charge of a condensator decreases exponentially in time with a constant in time τ following the here-under relation:

$$q_{(t)} = q_{(0)} e^{-t/(RC)} \tag{1.2}$$

Where τ = RC and $q_{(0)}$ indicates the charge of the condensator at the moment t=0, while R indicates the resistance of the dielectric (equal to the inverse of resistivity) and C the capacity of the above mentioned condensator. A plain condenser is formed by two conducting plain surfaces which are in parallel with a d distance (dielectric thickness); if above two surfaces electric charges with + σ e – σ density are placed in a uniform way, the difference in potential between the plates is $\Delta V = \sigma\ d/\varepsilon_0$ respectively. This result is valid only for a real plain condenser and the approximation is as better as the dimensions of the plates are larger compared to their distance and this helps our approach considering the involved thicknesses. If S points out the area for each plate with total charges + σS and –σS respectively, it makes:

$$C = \varepsilon\, S / d \tag{1.3}$$

Where

$$\varepsilon = \varepsilon_r \varepsilon_0 \tag{1.4}$$

Where ε points out the dielectric constant or dielectric conductivity that reflects the macroscopic behaviour of the dielectric when electrostatic fields are present (for glass it fluctuates from 4÷10). A last problem is given by the fact our dielectric model is polar, because in the layers near to metal it keeps a negative charge and this fact means that, after proper mathematical transfers, a new χ factor appears which represents the electric “susceptibility”:

$$\varepsilon = \varepsilon_0 (1 + X) \tag{1.5}$$

The electric susceptibility for polar dielectrics is function of temperature, therefore the discharge time of the electrostatic powder depends from temperature.

By summarizing, the time requested by the electrostatic powder for loosing its charge and adhesion depends on parameters which are directly related to discharging time, like Temperature and Resistivity, besides environmental conditions, like air moisture which increases dielectric conducibility and increases discharging time of the powder adhered to the body.

You can find here-under a comparative table Temperature/Air Humidity, experimental obtained by the studies of Mr. Quadri /WAGER ITEP SPA, who indicates environmental conditions the most suitable for enamelling:

Tab. 1

CONTENUTO IN ACQUA (grammi) PER KG DI ARIA SECCA A PRESSIONE NORMALE

Legenda :
ε (%) – Umidità relativa
t (°c) – Temperatura dell' aria
(gr.) – Quantità di acqua per kg di aria

ε % →

t °c ↓	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%	100
15°C	W (g) → ↓ 0,5	1,0	1,6	2,1	2,6	3,2	3,6	4,1*	4,8	5,3	5,9	6,3	7,0	7,5	8,0	8,6	9,0	9,6	10,1	10,6
16°C	0,5	1,1	1,7	2,2	2,8	3,4	3,9	4,5	5,1	5,7	6,3	6,9	7,4	8,0	8,6	9,1	9,7	10,2	10,8	11,3
17°C	0,6	1,2	1,8	2,4	3,0	3,6	4,2	4,8	5,4	6,0	6,7	7,3	7,8	8,5	9,1	9,8	10,2	10,9	11,4	12,1
18°C	0,6	1,3	1,9	2,6	3,2	3,8	4,5	5,1	5,8	6,4	7,1	7,8	8,4	9,0	9,7	10,4	11,0	11,6	12,2	13,0
19°C	0,6	1,3	2,0	2,7	3,4	4,1	4,8	5,4	6,2	6,9	7,6	8,2	8,9	9,6	10,3	11,0	11,7	12,2	13,0	13,8
20°C	0,7	1,4	2,1	2,9	3,6	4,4	5,1	5,8	6,4	7,3	8,1	8,8	9,5	10,3	11,0	11,8	12,4	13,1	14,0	14,7
21°C	0,7	1,5	2,3	3,1	3,8	4,7	5,4	6,2	6,8	7,8	8,6	9,3	10,1	10,9	11,7	12,4	13,2	14,0	15,0	15,7
22°C	0,8	1,6	2,4	3,2	4,0	5,0	5,8	6,6	7,3	8,3	9,1	10,0	10,8	11,6	12,3	13,2	14,1	15,0	16,0	16,7
23°C	0,8	1,7	2,6	3,4	4,3	5,3	6,2	7,0	7,8	8,7	9,7	10,6	11,5	12,2	13,2	14,0	15,0	16,0	17,0	17,8
24°C	0,9	1,8	2,7	3,6	4,6	5,6	6,6	7,4	8,3	9,3	10,3	11,3	12,2	13,0	14,0	14,9	16,0	17,0	18,0	18,9
25°C	0,9	1,9	2,9	3,9	4,9	5,9	7,0	7,9	9,1	9,9	10,9	12,0	13,0	13,8	14,9	15,9	17,0	18,0	19,0	20,0
26°C	1,0	2,0	3,1	4,2	5,3	6,3	7,3	8,4	9,5	10,5	11,6	12,8	13,8	14,7	15,9	16,9	18,0	19,0	20,2	21,4
27°C	1,1	2,2	3,3	4,4	5,6	6,7	7,8	8,9	10,2	11,1	12,3	13,5	14,6	15,6	16,9	18,0	19,2	20,2	21,5	22,8
28°C	1,1	2,3	3,5	4,7	5,9	7,1	8,3	9,4	10,9	11,8	13,1	14,3	15,5	16,7	18,0	19,0	20,3	21,7	23,0	24,2
29°C	1,2	2,4	3,7	5,0	6,2	7,5	8,8	10,0	11,6	12,4	13,9	15,2	16,5	17,8	19,0	20,2	21,6	23,0	24,6	25,7
30°C	1,3	2,6	3,9	5,3	6,6	7,9	9,2	10,6	12,0	13,3	14,8	16,0	17,5	18,9	20,1	21,4	23,0	24,3	25,9	27,2

An adequate content of water varies from 4 and 9 grams per Kg of dried air, area indicated between two lines in bold in the table.

Differences in adhesion could be attributed to these variations that could be noticed between summer and winter periods or wet and dry days, without having variations in production cycle, both from the manufacturer and the customer.

The velocity by which the charge leaves the piece is very important as the adhesion should be enough the piece is manipulable and the powder does not fall before being vitrified in the furnace.

Production control and Application Proportion (PRC)

The reological controls made on the electrostatic powder are influenced by many factors.

In order to strongly reduce them, they are made in an air-conditioned laboratory, where both temperature and humidity of the air could be changed.

The typology of the controls did not change a lot with time: fluidity, adhesion, resistivity, fineness (45µm cone or laser granulometer) and transfer efficiency (PRC) are the parameters for the application of the product in a specific plant. Pls remember, not all above mentioned parameters have the same importance in a rheologic control, for example the efficiency in transfer, that represents an index for the quantity of product settled on the piece in the unity of time, is often considered marginal and does not appear in conformity certificates.

The aim of this work is to point out the importance of the transfer efficiency during the production control of the electrostatic powder and in particular of the boilers enamelling, in order to keep the distribution of the glaze over the finished piece under control.

This value can be connected to three different aspects of the enamelling based on the object to be enamelled:

- On plain surfaces the PRC is connected to the optimization of the enamelling thickness.
- In areas with deep pressing like for example gas cooker and baking oven the PRC is an essential requirement for overcoming “Faraday’s cage” and uniform applying in the hollows.
- For boilers, given the geometry and the application system, a good PRC leads to the application of an uniform thickness above all the surface.

Therefore the PRC is fundamental for every pieces should be submitted to the enamelling process. In this work we studied PRC values related to boilers, by examining its reliability as applicative parameter for calculating the distribution of the enamel on the piece. Furthermore we tested both stability to ageing process and excessive bubbles of all our tests. We are doing similar evaluations for all pieces to be enamelled, in order to have a complete picture of the influence of this parameter on the distribution of the powder based on the piece to be enamelled in future.

For making this test we industrially produced some powders for boiler with different organic components, in order to obtain 7 different products with different transfer efficiency values and after a careful evaluation, we applied them in an industrial plant, in order to establish, through the analysis of finished pieces, with an equal working conditions, the real differences among the various samples.

Preparation of the samples

The powder samples were prepared in an industrial mill by adding organic additives so that the requested variation of transfer efficiency parameter was obtained without modifying other application parameters in a substantial way.

During the preparation of the samples the following parameters remained unchanged:

- The mix of frits,
- Grinding parameters,
- Application values which are different from the parameter of our interest.

In the following table you can find the main application parameters of the powders taken into consideration:

Tab. 2

Test	PRC	Fineness
1	21.8	15.9
2	24.4	16.1
3	26,5	15,5
4	29,5	15,6
5	32,1	15,8
6	42,5	15,8
7	54,5	16,2

Experimental procedures

Evaluation in laboratory

The test for the laboratory evaluation of PRC is in defining how much enamel should be applied on a 20x20 cm sheet keeping remaining parameters fixed; the distance between piece and spray-gun, applied voltage, the parameters for the adjustment between air-enamel and application time (30 sec.) are fixed in advance.

Pls find here-under a photo with the application system:

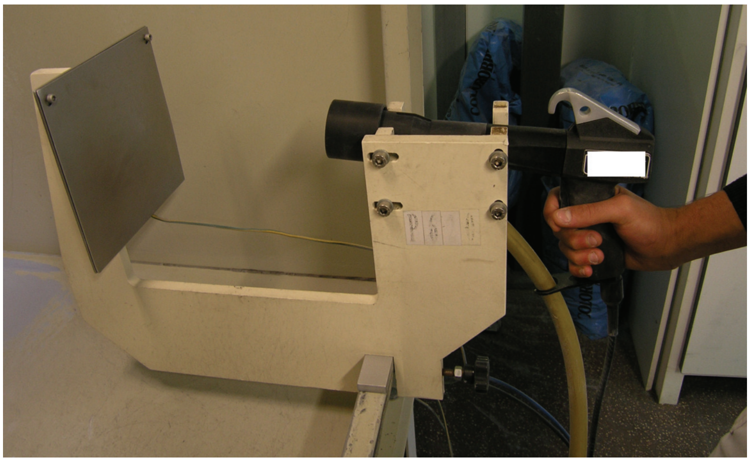


Fig. 3

Requested materials

- Application booth with device for testing bearing
- 20x20 cm inox steel sheet
- Cronometer
- $\geqslant$0,01 g precision balance
- Environment with 25°C and 35% humidity

Test realization

1. weight the sheet and hang it to the bearing
2. put 1.5 kg. enamel in fluidyifing box, that like in the industrial plants keeps the enamel in suspension and allows a constant flux of enamel flow towards the application spray-gun.
3. adjust the spray-gun for applying the enamel as
   - Voltmetro kV 70
   - 2 bar air pressure
   - 1.5 bar air pressure in the fluidifying box
4. apply the enamel onto the test piece for 30 seconds, placing the spray-gun at a fixed distance on the specially provided bearing.
5. weight the sheet.
6. From the weigh difference you calculate the weigh of the enamel settled in 30 seconds

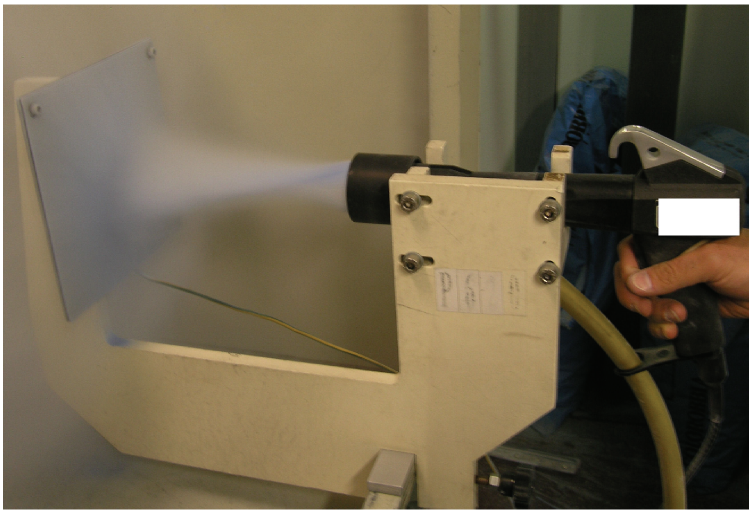


Fig. 4

Interpretation of the results

The value of the transfer efficiency is given by the weigh of the enamel which adhered to the sheet and is expressed as:

PRC = grams of settled enamel

In parallel this study was also carried out by using different voltages (40 and 0 kV); by a laboratory test it simulates the behaviour of the enamel, when applied on pieces with a deep pressing. By decreasing the potential difference, the powder results less charged and its behaviour is the same as when applied on pieces with the presence of " Faraday's cage" effect which does not allow the penetration of the powder onto the piece to be enamelled. By this way we can obtain an evaluation for the transfer efficiency which can be the most suitable for the piece to be enamelled for other kinds of products too.

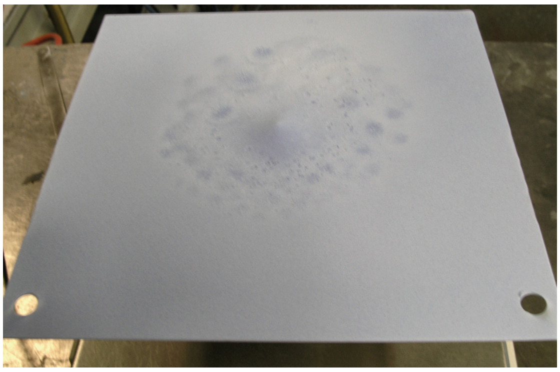


Fig. 5

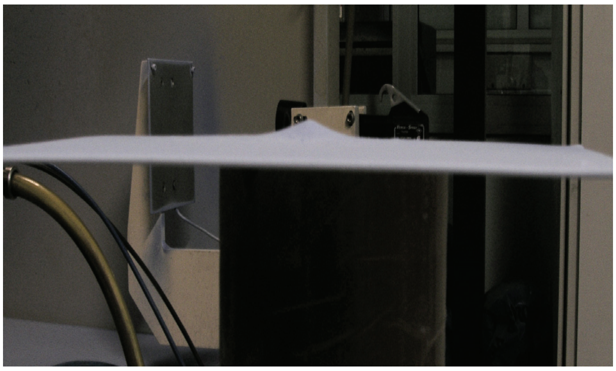


Fig. 6

All evaluations are carried out in the electrostatic powders control laboratory which has a constant temperature 25°C with 35% humidity. As already told, the environmental parameters influence the evaluation of an electrostatic powder in a relevant way.

Every single measuring is repeated for 5 times and for each one it was calculated an average value with a standard deviation of 4.2%.

You can find obtained values in table nr. 2.

Industrial evaluation of developed powders

The test was carried out by 80 liters boilers by enamelling 10 boilers for every kind of powders.

During enamelling the application program of the cabin was not changed so that we could judge the examined parameter in the most reliable way.

In order to facilitate the reading of these data the boiler surface was divided into 5 zones by making a mapping for the thicknesses and relating the average value.

Thanks to this industrial application we could connect the following parameters:

- PRC and enamel thickness
- PRC and ageing of electrostatic powder
- PRC and bubble structure

PRC and thickness of the enamel

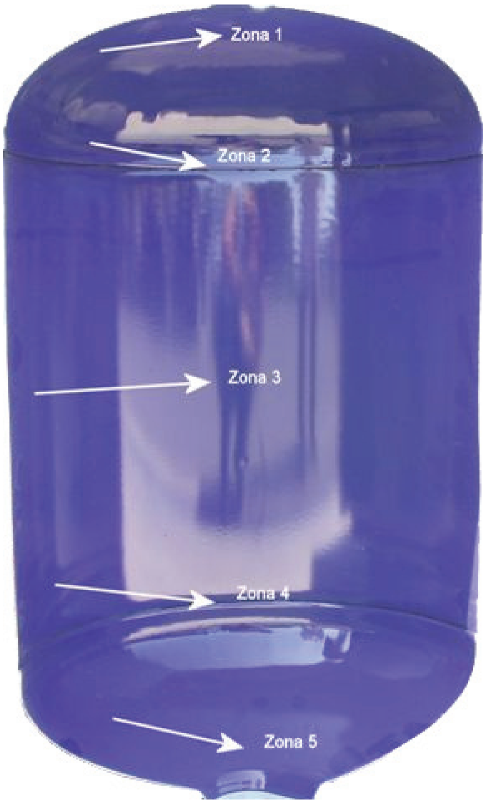


Fig. 7

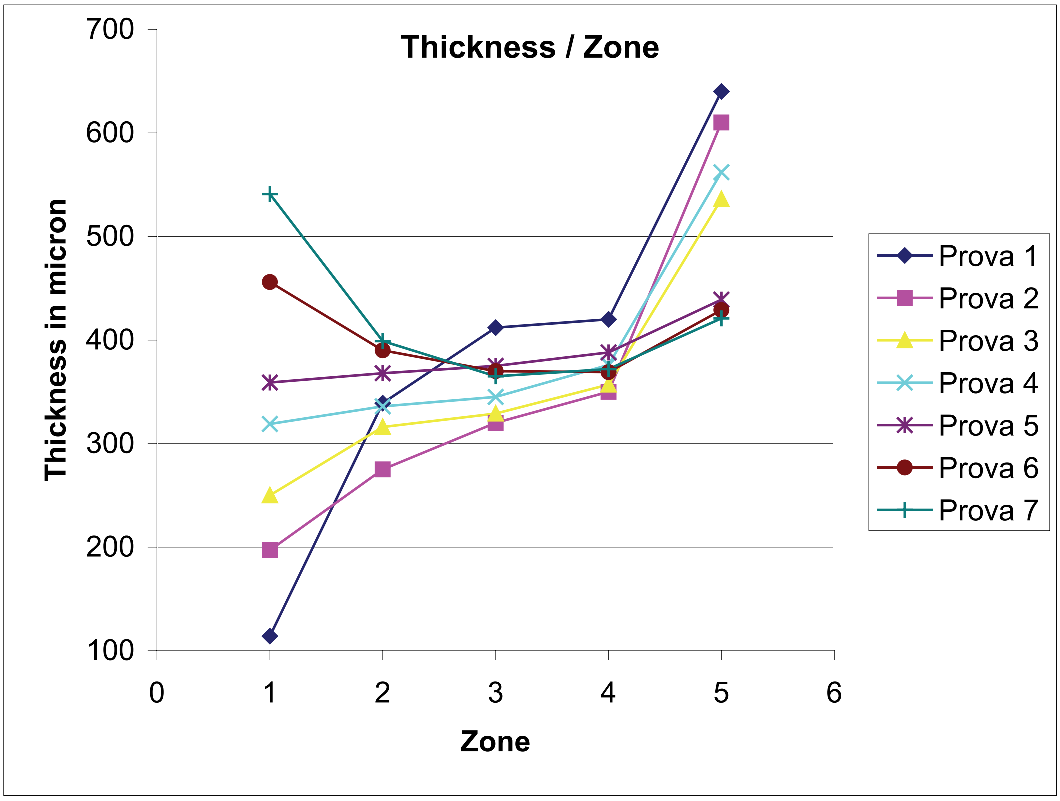
Zone 1: It concerns the upper cap.
Zone 2: It concerns the space portion between the upper welding.
Zone 3: All the part concerning body
Zone 4: It concerns the space portion between the inferior lower welding.
Zone 5: The bottom part of the boiler.

By analizing the thicknesses in the areas pointed out for the various enamels we obtained the following results:

Tab. 3

Sector	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7
1	114	197	250	319	359	456	541
2	339	275	316	336	368	390	399
3	412	320	329	345	375	370	365
4	420	350	357	376	388	369	372
5	640	610	536	562	439	429	421

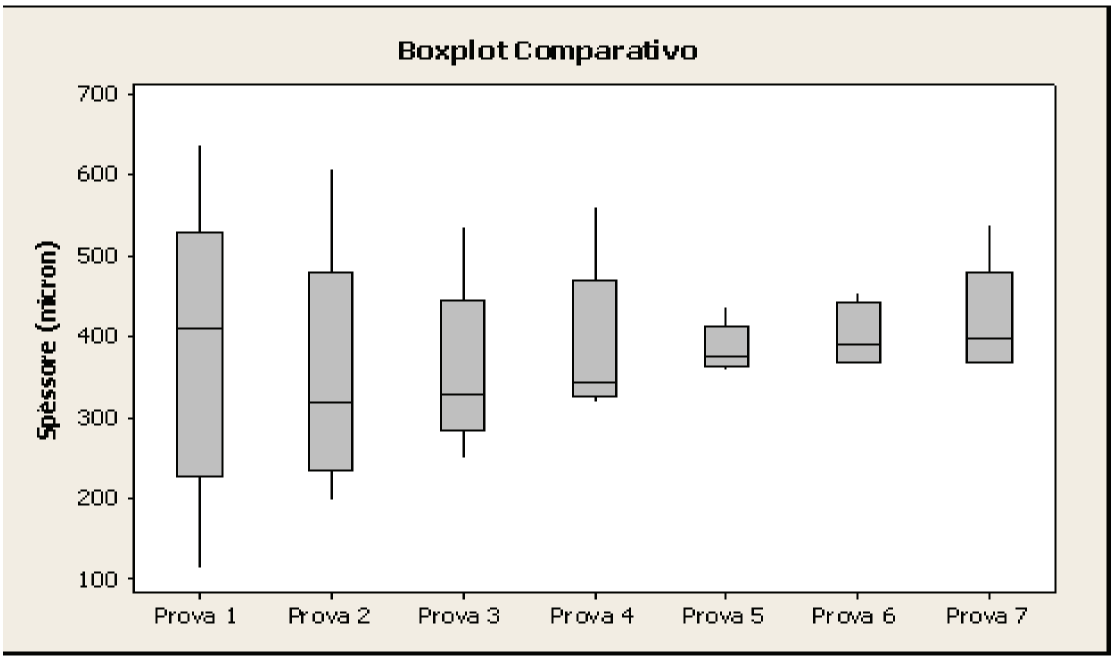
By putting these data into a graph we obtained:



Graf. 1

As we can easily estimate from graph 1, test nr.5 presents the greatest stability in thickness on all the surface of the boiler.

To better show it, we are transferring STD deviation for the thicknesses noticed during the various tests:



Graf. 2

In order to statistically analyze the thicknesses of the enamel applied during the various tests, e used the graphic representation “boxplot”. By this graph we can compare the distribution of the various series and in particular we can see test nr. 5 has the lower dispersion, that is the one where median and quartiles are similar values. On the other side we can observe first four tests give thickness values very unstable.

Compared to the other value, a lower dispersion is clearly indicative of a more uniform distribution in the thickness of the enamel inside the boiler. Other distributions, some of them valid, present a distribution of the thickness on the piece which is less uniform and could lead to colour changes and, in worst cases, burns or greater thicknesses with enamel chip off.

Therefore we understand only when the transfer efficiency comes under a certain values range we have an optimal distribution of the enamel inside the boiler. The control laboratory has a values range for the parameter of our interest. We experimentally tested that a fluctuation +/-7% for tested parameter does not influence the distribution of the enamel inside the boiler in an essential way. We use this interval as limit for control acceptance, so that we can always guarantee a good stability in application.

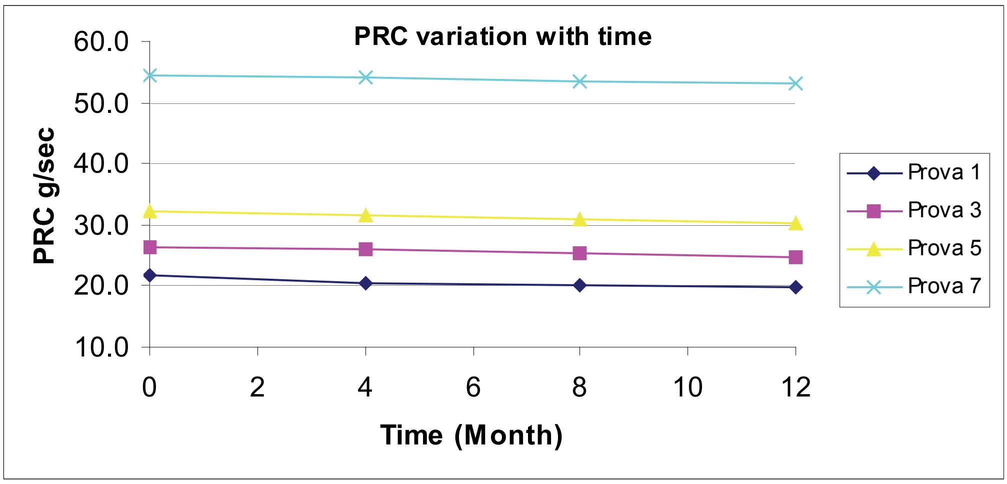
PRC and ageing of electrostatic powder

Talking about electrostatic powders another parameter to be considered/ kept in mind is the ageing; and actually the application parameters of these products change with time. Therefore as following step, we verified the variation of reological parameters with time in general, and the transfer efficiency in particular. For this reason the industrial samples were kept in the store and tested again at fixed periods (4, 8, 12 months) in laboratory, following the same method as previously described and obtaining the results stated in table nr.4

Tab. 4

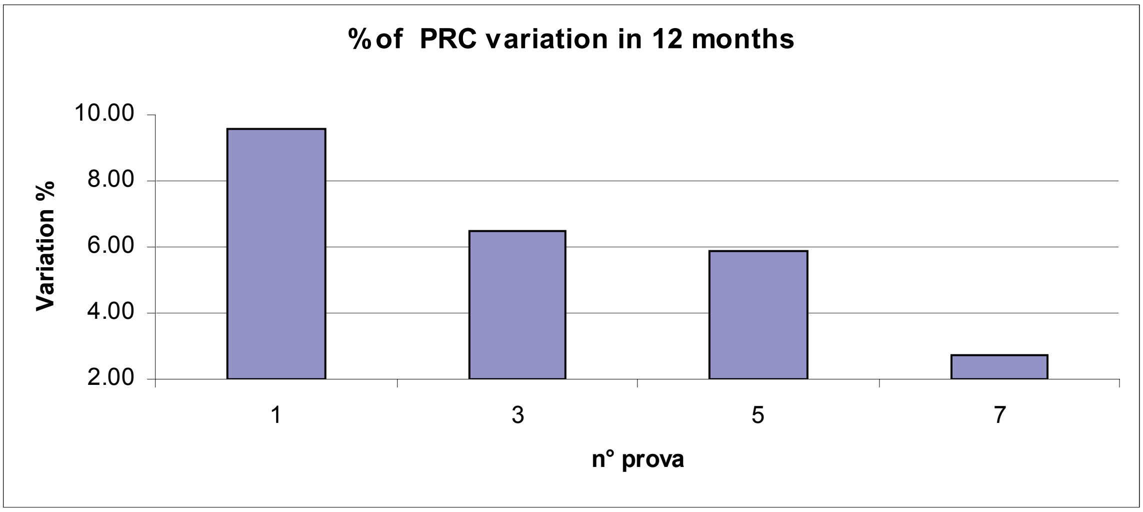
Time (months)	0	4	8	12	Variation %
Test 1	21.8	20.6	20	19.7	9.6
Test 3	26.5	25.9	25.2	24.8	6.5
Test 5	32.1	31.6	30.9	30.2	5.9
Test 7	54.5	54.1	53.6	53	2.7

Carrying the values in graph we obtain:



Graf. 3

The graph shows the loss in production application capacity both linear and with time, notwithstanding we cannot value the exact difference in percentage. This latter could be estimated in table nr.3 and following graph.



Graf. 4

From these results it is evident the ageing of powders involves a variation in transfer efficiency according to the composition of the organic part. From settled values we can point out a powder with a greater transfer efficiency varies such properties to a less pronounced extent with time. Such products having an “exaggerated” thickness on the upper part of the boiler, show other kind of problems like enamel chip-off or powder drops before the tank enters into the furnace.

In parallel the products with lower PRC values show a greater variability, but also (at the beginning) the thickness was not homogeneous.

For these products the “ageing” cause a further worsening of the quality of the powder.

PRC and bubble structure in enamel

Products with a well-determined value in transfer efficiency, which show an “ideal” distribution in powder, result the ones which keep a very good applicability with long time, despite an unavoidable variation with time.

On the boilers we cut, to carry out thickness mapping, samples were taken to undergo to SEM analysis. This test is necessary for evaluating the enamel bubble structure, essential requirement for the quality of a formula. An enamel with more bubbles is inferior in quality, having more empty space, shows less resistance to chemical attack. For this reason we made sure the product with a determined transfer efficiency did not interfere with other quality parameters.

We obtained the following results:

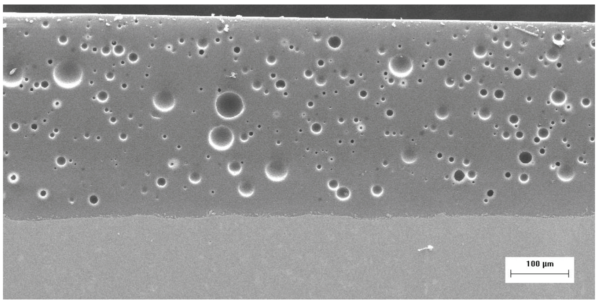


Fig. 8 test 1

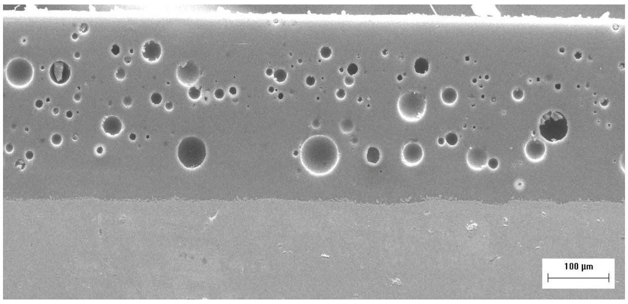


Fig. 9 test 2

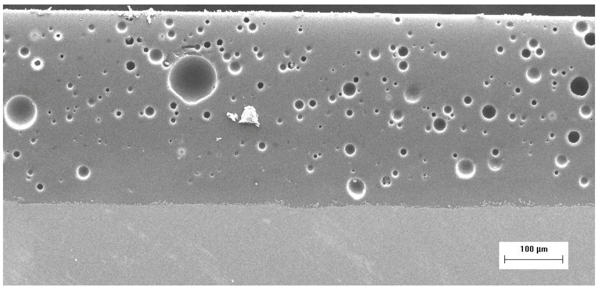


Fig. 10 test 3

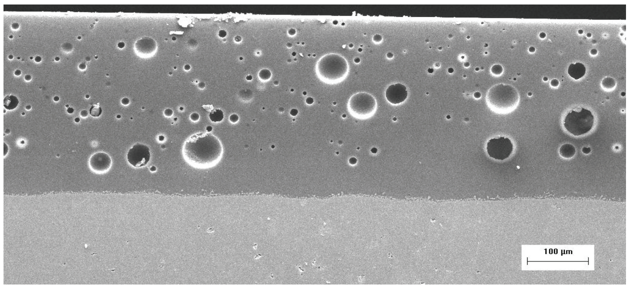


Fig. 11 test 4

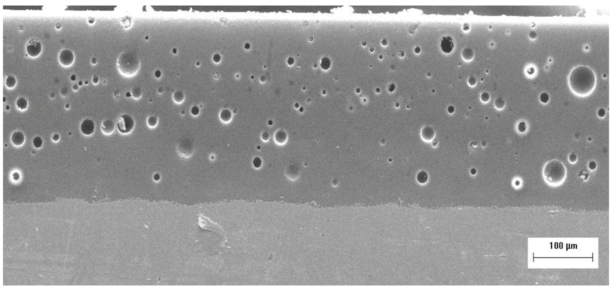


Fig. 12 test 5

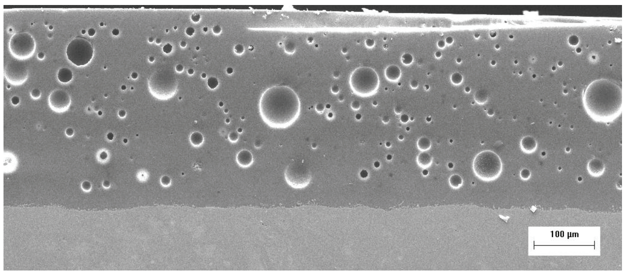


Fig. 13 test 6

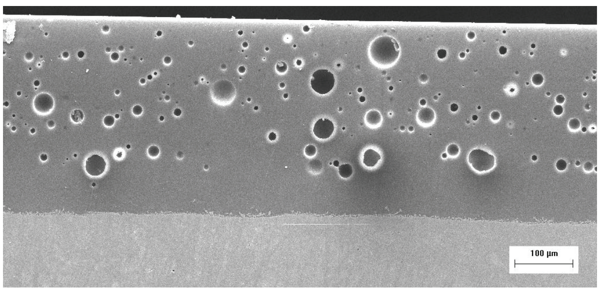


Fig. 14 test 7

As we can see the average bubble structure for series 1 to 6 shows a uniform distribution of little bubbles which gives a solid structure to the enamel, while the tests with an higher PRC have greater bubbles.

Besides from the other images, it comes out, having especially high values of transfer efficiency allows us, neither reaching an homogeneous distribution, nor a good bubble structure of the enamel.

Conclusions

All carried out tests make us to come to the conclusion the Transfer Efficiency is an applicative parameter which is very effective for estimating the constancy in distribution of the enamel inside the boiler.

Furthermore tested products show a precise correlation among:

- PRC and thickness of the enamel
- PRC and ageing of the electrostatic powder
- PRC and bubble structure

Making a summary of three above mentioned parallels we come to the conclusion PRC value 31± 2 is the optimal value for having a good distribution of the product inside the boiler, a good stability of the electrostatic powder with time and a good bubble structure.
Obviously what described till now is the fruits of a study conducted on a single industrial plant. The PRC optimal value should be studied as a function of the plant and customer's requirement, in such a way as to have the right value for all the properties of an electrostatic powder.

Identify an index parameter for the good distribution of the powder offers considerable advantages to the producers but also greater quality guarantees to the customer.

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