THE USE OF DESIGN OF EXPERIMENTS TO IMPROVE QUALITY IN A CASTING PROCESS – MOLD PAINTING CASE STUDY

Christian Egidio da Silva, christianegidio@gmail.com
Instituto Tecnológico de Aeronáutica (ITA), 12.228-900, São José dos Campos, SP, Brasil
Gerdau Aços Especiais, 12.442-260, Pindamonhnaganba, SP, Brasil

Luiz Carlos Silidônio Júnior, lui.junior@gerdau.com.br
Carlos Leandro Leite Pereira, carlos.pereira3@gerdau.com.br
Amir Rivaroli Júnior, amir.rivaroli.@gerdau.com.br
Gerdau Aços Especiais, 12.442-260, Pindamonhnaganba, SP, Brasil

Abstract.*The present work was developed to understand the influence of raw material on the properties of one specific dressing type used in a casting process in order to improve its quality. This kind of painting is used to protect the metallic mold during the casting process against damages and to control the metal cooling inside the mold. After knowing the real influence of each material it is possible to define the best process parameters in order to become the process more efficient and strong. It was applied a design of experiments with three factors and three levels to optimize the tests. The proportion of zirconium silicate (refractory constituent), aluminum monophosphate (bond-activating agent) and sodium bentonite (bonding material) were changed. The following tests were performed: suspension, viscosity, density and pH. The results showed that zirconium silicate and sodium bentonite present, in general, the same behavior in terms of viscosity – measured by density, flowing time and suspension. Aluminum monophosphate presents an opposite behavior in relation to sodium bentonite and zirconium silicate. The addition of sodium bentonite contributes to the viscosity increasing, potentiating the effect of zirconium silicate. Aluminum monophosphate influences on the acidity of material too much. The addition of sodium monophosphate reduces the viscosity. The individual effect of zirconium silicate and sodium bentonite is minimized by the aluminum monophosphate. The results suggest that the suspension test isn't an adequate practice to evaluate the painting viscosity because it could lead to a wrong understanding of the result.*

Keywords*: casting, painting, DOE, zirconium silicate*

1. INTRODUCTION

When we are confronted with a decision we must choose between at least two alternatives. The choice we make depends on many factors but in quality driven operations, the most important factor is the satisfaction of the customers. The quality of a product is the result of a combination of factors. If that combination is suboptimal, quality will suffer and the company will lose as a result of rework and repair (Bass, 2007).

In accordance to Bass (2007), the Best operations' decisions are the result of a strategic thought that consists in conducting several experiments, combining relevant factors in different ways to determine which combination is the best. This process is known in statistics as Design Of Experiment (DOE). Due to several factors which affects the quality level of the products and services, it is necessary to know how the input factors and their interactions affect the response variable.

The new worldwide competition way requires that the companies to be compromised with continue and complete product, process and manpower improvement. They were necessary methods which can be used to conduct all the company to a correct direction in order to reach the goals (Robles Júnior, 2003). Silva (2002) shares the same thought about the contemporaneous competition, technology and management rules which requires a lot of changes on the way to measure and manage its business. In this context the investment on training and process improvement become fundamental and necessary to the company success.

In accordance with Laszlo (1997) it is assumed by top management that quality improvement related to the products and services offered raises the cost of operation above the current levels. This view is not merely simplistic, but it is erroneous. It is based on the assumption that improvements inherently involve higher expenditures. It can be simply demonstrated that not all quality improvements carry higher price tags – higher efficiency may be obtained, in some cases by simplifying tasks, thereby reducing costs. Moreover, in certain cases of quality improvements, the added costs associated with the quality improvement are outweighed by the financial benefits derived from the changes – the cost of conducting design reviews may be considerably less than complications arising from design errors.

The quality cost approach is based on the balancing of the cost of assuring quality against the costs associated with problems attributed to a lack of quality. The goal of quality improvement is to minimize inefficiencies and waste. The savings could be translated into added margin that increases shareholder value, and/or the savings could be passed along to the customers in the form of a price reduction (Laszlo, 1997).

The present work was developed to understand the influence of raw material on the properties of one specific dressing type used in a casting process in order to improve its quality and productivity. After knowing the real influence of each material it is possible to define the best process parameters in order to become the process more efficient and stronger.

2. THE CASTING PROCESS

2.1. General description

The casting process consists on a metal melting and its pouring inside a mold. This mold normally is manufactured with sand. It is used inside the mold a pattern which will reproduces the item to be cast during the molding process. After having packed the sand in the molding flask, the pattern is removed and the resulted shape is finished off. The molten metal is poured into the mold. There are many process parameters which shall be controlled during and after casting to guarantee a good product: sand mold hardness, temperature of molds, dressing density, dressing thickness.

The mold painting process is described as follows:

(a) The metallic mold is mechanical cleaned to remove all the residues of previous casting.
(b) The mold is pre-heated up to around 350^{o}C and after reaching this temperature the tooling is maintained at this temperature for 21,600s (6h).
(c) After concluding this pre-heating cycle the molds is taken out from the furnace and start the painting process.
(d) The operator weighs the specific painting quantity in accordance to the casting project, which is calculated as a function of the internal mold dimensions and the material to be casted. It is necessary to clarify that the painting must be previous analyzed and approved before using.
(e) The mold is put over a centrifugal machine and starts to rotate until reach a specific speed. In this moment the painting is put inside a kind of funnel and all the content is transferred to the mold. Because the mold temperature the water of painting evaporates and the mineral constituent (zirconite) remains fixed on the internal diameter of mold.
(f) After the application, the painting thickness is verified using specific equipment and the temperature is monitored until the instant to casting. The final thickness and the temperature are controlled.
(g) The mold back to the furnace once more to guarantee that the water will be totally evaporated. This equipment waits for the moment to assembling the tooling for casting.

The mold is allowed to cool and after the metal solidification and the total cooling it is carried out the piece stripping. In this step the piece is stripped off from the mold.

Immediately after its stripping, the pieces are submitted to a non destructive inspection (X-Ray, ultrasonic testing, magnetic particle, penetrating liquid, microscopic analysis) to check the existence of discontinuities and to evaluate the integrity of obtained piece.

On the sequence the pieces are submitted to a heat treatment and after concluding this operation, they are conducted inspections like hardness and residual stress measurements.

Finishing these inspections the machining process started. It is common to conduct some audits on the machining steps during the process to guarantee that all the real dimensions are in accordance to the specified parameters. After concluding this machining it is performed a final inspection – ultrasonic inspection, hardness measurements and magnetic particle – and the piece is read for shipment.

It is noted that along all the manufacturing process there are many inspection steps, which are necessary to guarantee perfect product conformity to satisfy the customer.

2.2. Painting on casting process

The painting used to a casting process shall present a great thermal insulation capacity to permit changing on the heat transfer mechanism delaying the metal cooling. Additionally it is necessary that the painting presents resistance to deformation on high temperatures.

The mineral constituent of a painting can be classified into “carbonaceous materials” (graphite, grated coke, carbon black), “silicates” (aluminum silicate, calcium silicate, magnesium silicate, zirconium silicate) or “oxides” (quartz, magnesite, rutile, spinel). These constituents present high melting temperatures, normally higher than 1,600^{o}C and sometimes reach 2,000^{o}C or more. Considering the silicates, the zirconium silicate ($ZrSiO_4$) is the material most used. Olivine (Mg_2SiO_4), magnesite ($MgCO_3$), mulite ($3Al_2O_3.2SiO_2$) and chamote ($Al_2O_3.SiO_2$) are used but with a lower percentage. Chromite ($Al_2O_3.Cr_2O_3.FeO$) is still used, presenting good surface finishing quality but with a cost too high. It is possible to use others refractory materials with low melting point phases to become the painting more resistant to deformations on high-temperature.

The vehicle is a liquid that maintains the mineral constituent disperse on the mixture, permitting its application on the mold surfaces. Basically it is possible to use water or industrial alcohol. The great advantage of water is its low cost and the fact that doesn´t present environmental risks. Water is more difficulty to be removed than the alcohols due to its slowly evaporative process – normally requires a consumption of energy to promote its evaporation. The most common alcohol is isopropanol.

The suspension agent delay or exclude the sedimentation process of mineral particles in suspension on the vehicle. This material, when in repose on the vehicle, makes a structure that maintain the mineral particles in suspension, avoiding an excessive penetration of vehicle on the mold – due to its absorption and swelling – contributing to the formation of a homogeneous painting thickness. The cheaper suspension agent is "sodium bentonite". It is possible to use some marine algae (alginates) and cellulose derivative (carboxymethyl cellulose).

The bond-activating agents are responsible by the adherence of mineral particles on the mold (substrate) and the mutual cell cohesion among the particles on the painting thickness. There are organic and inorganic types.

3. MATERIALS AND METHODS

The painting used to this study consists on a mixture of a mineral constituent (zirconium silicate), a vehicle suspension component (water), a colloidal suspension agent (sodium bentonite) and a bond-activating agent (aluminum monophosphate).

3.1. Design of experiments

Table 1 presents the design of experiments used to the present study.

Table 1. Parameters and levels analyzed for the mold painting process.

	Level		
Parameter	-1	0	+1
Zirconium silicate	125g	250g	375g
Sodium Bentonite	6g	12g	18g
Aluminum monophosphate	4g	8g	12g

3.2. Painting preparation

The experiments were conduct using different batches of painting prepared exclusively to this study. All the batches were prepared in laboratory with the same methodology of a real production scale. The quantities were adjusted to the experiment but the typical proportion between constituents was maintained. The mixing time was adjusted to the involved quantity on the batches.

It was defined a Design of Experiments of 3 factors and 3 levels to evaluate the real influence of each raw material and its interaction on the properties of one specific dressing type in order to improve its quality. The "zero" level of matrix is the standard raw material proportion.

The painting batches were prepared as follows:

(a) Preparation of sodium bentonite gel in a beaker adding 160ml of potable water and the quantity of bentonite specified on the experiment. These constituents were maintained in mixing during 300s (5min). The water quantity was maintained because this constituent is not a scarce resource.
(b) The bentonite gel was maintained in repose for a minimum of 43,200s (12h), which is its typical swelling time. After concluding this time, in another recipient, it was put 40ml of potable water and under mixing, the aluminum monophosphate budgeted on the experiment was added. This mixture was maintained in mixing for additional 60s (1min).
(c) They were joined the both mixtures (bentonite gel and water/monophosphate) and this suspension was maintained in mixing for 120s (2min).
(d) The zirconium silicate budgeted on the experiment was added to this mixture in a continuous mixing. After adding all the zirconite maintain this new mixture under mixing for additional 300s (5min). The painting is read to be analyzed.

3.3. Laboratory testing

3.3.1. Viscosity, density and suspension tests

Viscosity is the most important physical characteristic for a painting used to a casting process because defines the solid material tendency to sedimentation, the tendency of applied paint film to fissure during its drying process and determines what is the more convenient application method to be used.

Viscosity can be measured directly, through viscosimeters, or indirectly, through its consistency or density. It is possible to measure the painting consistency using its flowing time across a specific cup with shape and dimensions standardized – the flowing time is directly related to its cinematic viscosity – or its density – which is determined through an immersion densimeter.

On the present study the viscosity was evaluated through flowing time, using a flowing cup number 4, in accordance to CEMP-073 (2003), and the painting density, using a specific immersion densimeter, in accordance to CEMP-115 (2003).

It was still used a suspension test to analyze the sedimentation capacity after concluding 86,400s (24h) of painting preparation. It was taken a sample of each batch after its preparation and this material was put inside a graduated cylinder until a specific reference (volume). After 86,400s the sedimentation was measured and, comparatively, it was estimated the suspension capacity of each batch.

3.3.2. pH tests

The pH is used to evaluate the chemical behavior or tendency of each material in terms of its acidity or basicity. It was used as reference the document CEMP-121 (2003).

This test normally is used to analyze, after finishing the paint preparation, if along the time there was any variation on the mixture acidity. This fact could be an indicative that there is a real contamination due to the microorganisms' growth.

4. RESULTS AND DISCUSSION

4.1. Viscosity tests (by means of Flowing time analysis)

Figure 1 shows that zirconium silicate and sodium bentonite present an expressive influence on increasing of flowing time. The aluminum monophosphate addition contributes to a decreasing on flowing time.

This increasing on flowing time with sodium bentonite can be explained by the increasing on the refractory cells (zirconite + bentonite) displacement after water absorption, which difficult the painting flowing. After being in contact with water, the bentonite expands too much. Considering its enormous volumetric expansion after contacting water the refractory cells reduce its density. This fact conduct to an increasing on water displacement, which contributes to an increasing on flowing time.

The increasing on flowing time with zirconium silicate occurs due to the great quantity of refractory particles in the same volume (occurs an increase on particles mass to vehicle volume rate). Considering that the vehicle volume doesn't change and the recipient volume is constant, the increasing on the refractory mass conduct to a particle overlapping. These particles are compressed reducing its interstitials, which are fulfilled with other thinner particles. This new condition conducts to a reduction on the flowing rate because more particles need to flow out at the same time.

The results suggest that sodium bentonite effect is more representative than zirconium silicate effect. It is possible to infer that the increase of bentonite volume makes the refractory' cells more close each other. Considering that the bentonite has great quantity of water on its constitution after absorbing, due to the hydrogen bonding, it will appear a significant chemical interaction between the particles' cells (zirconite/bentonite). This proximity between cells conducts to an increase on the flowing time because it is very difficult to the cell's movement.

The zirconium silicate effect is minimized with aluminum monophosphate increasing, but not for all proportion. There are differences on the results depending on the studied level. This behavior is noted on the interaction graphs. The flowing time seems to converge to the same aluminum monophosphate level. The zirconite/monophosphate interaction effect is significant.

It was not observed any significant changing on flowing time to the monophosphate/bentonite interaction. Considering that aluminum monophosphate doesn't influence on density and due to the similarity on zirconite/monophosphate and bentonite/monophosphate interactions, these results suggest that aluminum monophosphate works in order to break the chemical bonding (hydrogen bonding) among refractory's cells, which could reduces the flowing time.

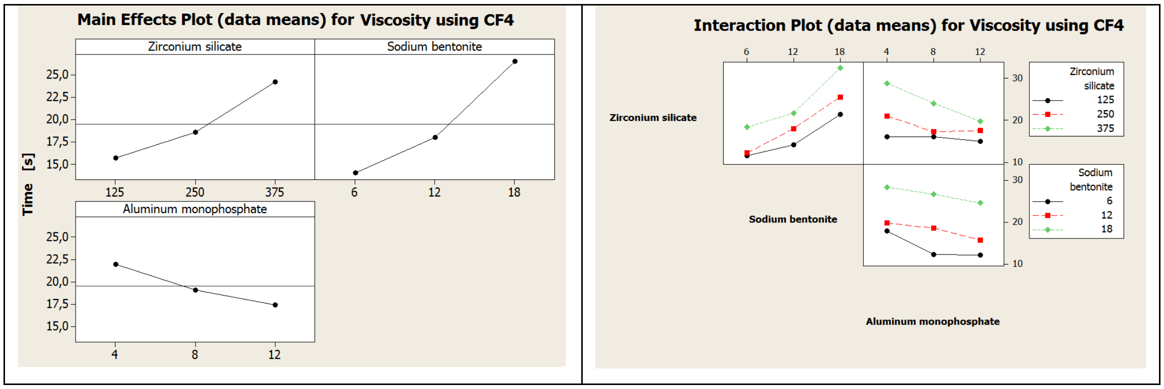

Figure 1. Main effect of constituents and its interactions on the flowing time.

4.2. Density tests

As can be seen on Fig. 2, aluminum monophosphate doesn't influence on density. The sodium bentonite presents a little contribution on changing density, but it is not too representative like that noted to zirconium silicate. Zirconium silicate is the constituent which really influences on density. It is necessary to clarify that the zirconium silicate density is the highest among these three studied constituent. So these difference on density is normal considering the individual difference among zirconium silicate, sodium bentonite and aluminum monophosphate.

There is no significant interaction among bentonite/monophosphate and zirconite/monophosphate. It is possible to see that there is a significant interaction among zirconium silicate and sodium bentonite.

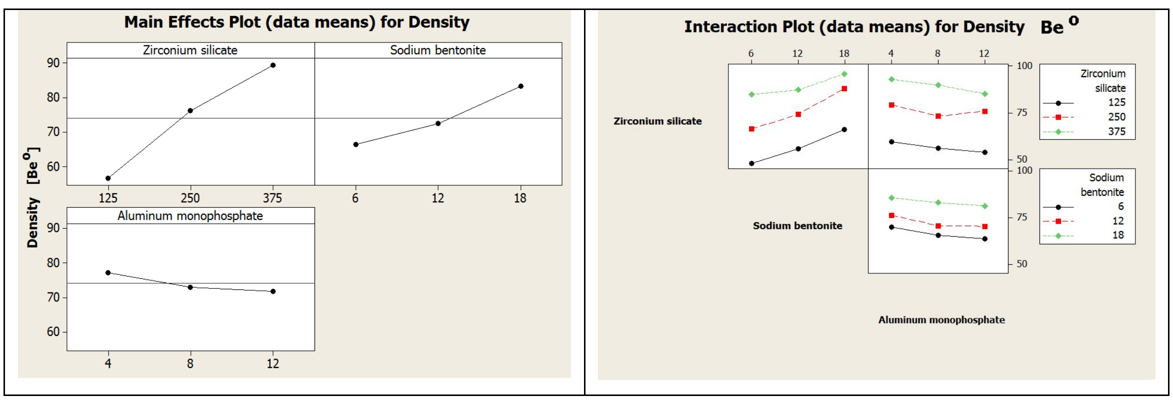

Figure 2. Main effect of constituents and its interactions on the density.

4.3. Suspension tests

The main effect behavior to "suspension testing" was quite similar to that noted to "density" and "flowing time".

Considering that a higher suspension column height after concluding 86,400s (24h) is an indicative that the deposition (sedimentation) of raw material is more difficult, it could be expected that the refractory material will stay in suspension for more time and due to that, the painting will be applied more homogeneously. This thinking is a mistake because when there is more refractory mass in the mixture, it is obvious that the suspension column height will be higher than that observed to the situation with lower refractory content. Therefore it is necessary be careful when this test is used.

As can be seen on Fig. 3, aluminum monophosphate doesn't influence on suspension. Sodium bentonite and zirconium silicate present a significant contribution on changing suspension.

There is no significant interaction among bentonite/monophosphate and zirconite/monophosphate. It is possible to see that there is a significant interaction among zirconium silicate and sodium bentonite.

The zirconite/bentonite interaction results show that sodium bentonite maximize the zirconium silicate effect. It is possible to see on Fig. 3 that the suspension column height is maximized with the sodium bentonite increasing. It is noted that a good suspension is obtained on the intermediated level for the both constituents, which suggests that is not necessary to work on the upper level of zirconite and bentonite to obtain a good result of suspension. These results are explained by the increasing on the displacement of refractory cells after the water absorption of bentonite.

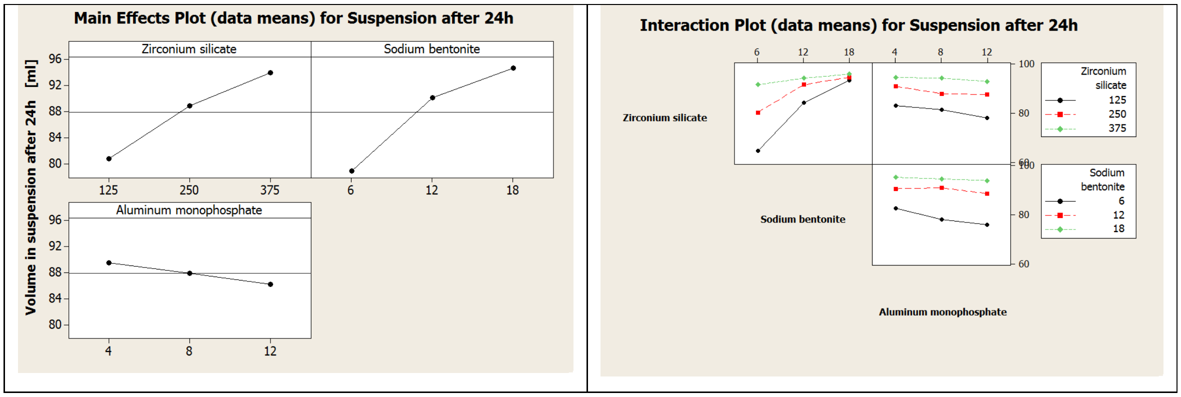

Figure 3. Main effect of constituents and its interactions on the suspension.

4.4. pH tests

It is possible to see on Fig. 4 that aluminum monophosphate is a very influential constituent on pH. The addition of aluminum monophosphate conducts to a pH decreasing.

The sodium bentonite has a little influence on pH. The addition of bentonite increase the pH until a specific value, after that no one significative changing on pH is observed. The zirconium silicate doesn't influence the painting acidity. It is considered normal pH between 2.3 and 2.9.

These results suggest that if it is necessary to change the painting pH, only the aluminum monophosphate and water content must be changed. However the water addition must be careful because other physical properties like density could be affected too much.

When they are analyzed the interactions between the raw materials, it is noted that there isn't any interaction with zirconium silicate. See that the results inside the same experiment levels are much closed. There isn't any interaction among sodium bentonite and aluminum monophosphate too.

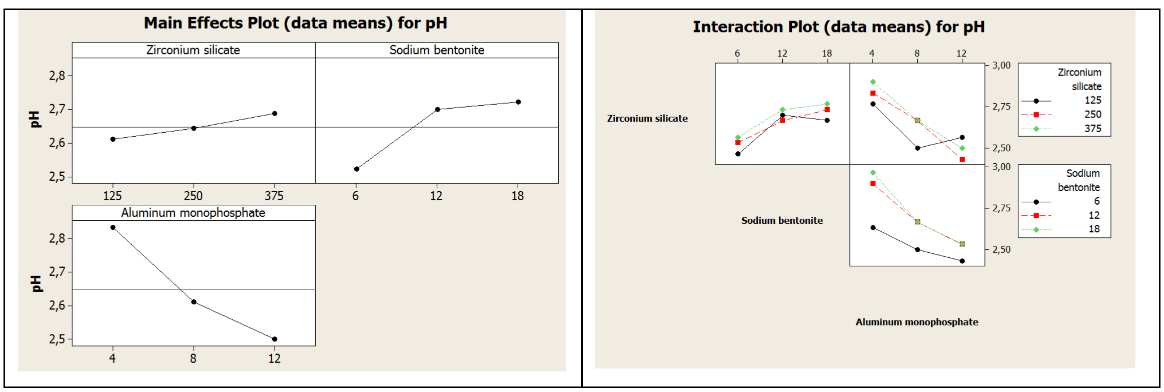

Figure 4. Main effect of constituents and its interactions on the pH.

5. CONCLUSION

It is possible to resume the influence of each constituent on the quality characteristics analyzed in the present study as follows: two arrows mean expressive influence and one arrow means small influence.

Zirconium silicate and sodium bentonite presented, in general, the same individual behavior. These constituents influenced with great similarity the studied parameters. Aluminum monophosphate presented an opposite behavior in relation to sodium bentonite and zirconium silicate.

The addition of sodium bentonite contributed to the viscosity increasing, potentiating the effect of zirconium silicate.

Aluminum monophosphate influenced on the acidity of material too much. The other constituents don't contribute to change the pH. If it is necessary changing the pH, only the aluminum monophosphate and water content must be changed. It is not necessary to change the sodium bentonite and zirconium silicate contents.

Table 2. Influence of each constituent on the quality characteristic.

	Density	pH	Flowing time	Suspension
Aluminum monophosphate	---	↓↓	↓↓	---
Zirconium silicate	↑↑	---	↑↑	↑↑
Sodium bentonite	↑↑	↑	↑↑	↑↑

Zirconium silicate and sodium bentonite had an expressive and positive influence on the viscosity – measured by density, flowing time and suspension. The addition of sodium monophosphate reduced the viscosity. The individual effect of zirconium silicate and sodium bentonite is minimized by the aluminum monophosphate.

The results suggest that the suspension test isn't an adequate practice to evaluate the painting viscosity. It could lead to a wrong understanding of results. The flowing time and density are much better practices and much more trustable than the first one.

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