USE OF DESIGN OF EXPERIMENTS TO IMPROVE THE PERFORMANCE OF DEGASSER NOZZLE REFRACTORIES

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ABSTRACT

A designed experiment was conducted to correlate the effects of purposeful changes made in the installation of a castable in a degasser nozzle and its field performance. Laboratory data was collected on the properties achieved by the castable as a result of these changes. This paper will describe the process of designing and carrying out the experiment.

FIELD EXPERIENCE

The Unit

Armco Advanced Materials Corporation installed a DH Degasser in 1970. Its main function is to aid in the final adjustments of the steel chemistry before it is taken to the caster.

Over the years, many changes have been made in the refractory lining of this degasser. Initially, the inside was lined with fused grain mag-chrome brick, which was subsequently downgraded to direct bonded brick.

The outside is mostly steel, but the section which is submerged in the molten metal and slag requires refractory protection. This section of the degasser is commonly called the nozzle (Figure 1), and it is the part which typically fails first. It is then exchanged to prolong the life of the rest of the vessel. A nozzle is made up of three layers: a monolithic on the outside, a supporting steel can in the middle which holds the refractories in place, and brick in the inside. (Figure 2)

The nozzle refractories are subject to erosion in the inside, slag attack on the upper outside section, and extreme thermal cycling on the tip. Thermal expansion of the supporting steelwork occurs at a different rate than the refractory expansion leading to stresses which have to be allowed for.

Consistent degasser nozzle life has so far been unattainable. Generally, a nozzle will be changed because of factors other than refractory failure, but occasionally the tip of a nozzle will crack and fall apart after very few heats. Post-mortems of refractories or operations and laboratory experiments have been unable to identify the cause of these failures. The impetus behind this work is to establish the factors which affect nozzle life and modify them to obtain predictable life.

The History

Previously published work[1] has shown that the most important factor affecting nozzle life is the number of extremely hot steel heats degassed consecutively. Laboratory work provided evidence that the freezing of alumina chrome plastic, previously used on the outside of the nozzle, causes the deterioration of its hot properties (Table I). As a consequence of this work, castables were tried on the outside.

Even though progress was being made in prolonging nozzle life, the unexplained failures continued. In order to obtain a better understanding of the factors which are important for nozzle life, a designed experiment was undertaken.

TAGUCHI METHOD[2]

Why a Designed Experiment?

One of the weaknesses of previous approaches was examining a very complex system with a one-factor-at-a-time method. This assumes that the natural variability of the factors other than the one under consideration is not significant. This approach also ignores the possibilities of significant interactions between factors. Through a designed experiment, many factors can be examined at once and interactions between factors can be studied at the same time.

Several mathematical constructs are available for designing an experiment. A full factorial experiment examines all possible combinations of the system. If there are fourteen factors to be examined at two values each, it would require 16,384 runs to study all possible combinations. If it is necessary or desirable to replicate each combination the number of runs goes up accordingly. And so does the cost. Other designed experiments use mathematical ingenuity to make intelligent predictions about the effects of individual variables and their interactions after only examining a subset of the total number of combinations. By reducing the number of runs, the cost is reduced proportionally.

There are many methods for designing experiments. The one chosen for this problem is that developed by Genichi Taguchi. The reason for this choice is simple - it is the one best understood and accepted by those carrying out the experiment and those to whom the results will be presented.

What is the Taguchi Method?

Define quality characteristic

The first step in designing a Taguchi experiment is to define the quality characteristic. The quality characteristic is the result(s) to be optimized. As with any experiment, picking the wrong characteristic, the testing will lead to inconclusive results. For this reason, it is sometimes effective to measure several quality characteristics, but analyze just one set of experiments. Then if one characteristic does not provide conclusive results, another can be investigated without rerunning the experiment.

Identify factors

Once the quality characteristic has been defined, the factors that effect that result must be identified. Interactions between factors must also be considered. The group developing the experiment must use engineering judgement in compiling the final list of factors. Care must be taken to include only the necessary factors as each additional one can increase the cost significantly.

Set levels

Each factor will need to be examined at least two different values or levels. Sometimes there is nonlinearity between factors and the quality characteristic and three levels or more are needed to define the relationship. Again, the more levels, the more cost. Usually two or three levels are sufficient to identify the important factors. A second experiment can be run to optimize the settings.

The levels should be set far enough apart to produce meaningfully different results but engineering judgement is necessary to know where the limits are.

Select matrix
Once the factors and levels have been identified, they must be fit into one of several matrices available for configuring the runs and the analysis. The structure of the matrices used by Taguchi is called an orthogonal array. Each of the matrices has a symmetry that allows comparing "apples and apples" when all the results are compiled. If any two columns are examined there will be an equal number of each combination of levels. The smallest matrix that will accommodate the selected number of factors and levels should be chosen to minimize the cost of the experiment.

Run experiments
Once the matrix has been selected, each row defines the set-up of a run. The levels for each factor defined by the rows must be followed for the experiment to be successful.

Predict "paper champion"
The results are tabulated and analyzed to determine the effect of varying the level of each factor. The factors that have the most influence on the quality characteristic are the most important to control. Those factors that have a moderate effect should be studied to determine the cost and benefits of selecting the more successful level. For the factors that have no significant impact on the quality characteristic, the level can be set based strictly on cost or convenience. This model, the "paper champion", is the theoretical prediction of the levels needed to optimize the quality characteristic.

Test theory
It should be noted that the paper champion was probably never investigated during the experiment. To find out it is necessary to predict an outcome for the paper champion and then run it, comparing the results to the prediction. If the appropriate engineering judgements were made during the selection of the factors and levels, then the results of running the paper champion will match the prediction. If the two do not match, some important factor or interaction was missed. This confirmation test should always be completed before any conclusions are made.

EXPERIMENT SET-UP

The experiment designed in this effort consists of work both in the field and in the laboratory. Previous experience left us with an uneasy understanding of what material characteristics constituted the best nozzle castable. The castable is exposed to severe thermal shock and a wide range of slag chemistries. It also has to support its own weight while hanging off the anchors of the substructure. One of the goals of this experiment was to shed light on how to optimize these properties.

The field results would be used to determine the best combination of factors to achieve a consistently long-lived nozzle. The laboratory tests would then characterize the materials used in the experiment and correlate their properties to their performance in the field. The results of this comparison should provide some direction toward further improvements in nozzle life.

Field Tests

Quality characteristic

The principle quality characteristic of the degasser nozzle is the point at which cracking first occurs. Traditionally, nozzle performance is measured in number of heats or contact time. The problem of using these measures for the experiment is that they are clouded by other variables that are of no interest. For example, the cracked nozzle can be repaired to extend the life thereby exaggerating the intrinsic performance of the material as cast.

A scale of one to five is used to rate the cracking of the nozzle. This measures the performance at points directly related to the failure mode and yet unaffected (or at least separable from) the variation in other factors. This helps to distinguish between the nozzle that lasted forty heats with a lot of patching from the one that failed at forty heats and the one that was taken off at forty heats but was still in good condition.

Factors and Levels

The factors and levels chosen are described below. The final selection was agreed to by a consensus of the masonry, research, and operating personnel involved.

For each factor we chose two levels. The levels were set by a combination of past experience and consultation with suppliers of the materials used in this experiment. One level was set at the supplier's recommendation and the other level as far as practical in the direction in which we were most likely to err (eg. too much water or too short mixing time).

"Material Used" - Past experience had shown that conventional castables deteriorated when exposed to a rapid sequence of heats. Low cement castables were less prone to failure. Since this was the current practice, a low-cement castable was chosen as one level. A no-cement castable was included to test the extreme condition of cement content.

"Curing Time" - Feedback from one supplier indicated that their material developed better properties when allowed to cure for 48 hrs rather than 24 hrs as had been our standard practice. Therefore, these were the two levels tested.

"Amount of Water Used" - Too much water in a castable leads to deterioration of properties.[3] Since the tendency is to put in too much water, we decided to test at the suppliers' recommended amount of water and at a higher water level.

"Mixing Time" - The material suppliers indicate that low and no cement castables require longer mixing times than conventional castables to assure a homogeneous mixture. We tend to shorten the time allowed for mixing in order to increase productivity and reduce the time in sometimes uncomfortable conditions. Mixing was carried out at the suppliers' recommendation and a shorter time.

"Expansion Allowance" - The different rates of expansion between the steel form and the castable must be allowed for.[4] The amount necessary and the design are not well understood. The current design uses a wax coating over the can and anchors. For the second level, additional expansion will be allowed by wrapping the can in ceramic fiber paper before dipping the assembly in wax.

"Time Vibrated" - Field experiences suggest that over-vibration is possible.[5] The levels selected for this factor were to vibrate only for a short time after each pour and to have the vibrators run during the entire cast.

"Condition of the Vibrators" - The effectiveness of the vibrators diminishes as the parts wear out, so they must periodically be refurbished. How often this must be done is not known. If it is an important variable, the additional cost for more frequent maintenance will be worthwhile. If not, money can be saved. Since it is not desirable to purposefully damage a vibrator, we will examine the effect of two small vibrators versus two small and one large vibrator.

"Number of Anchors" - While anchors are necessary to support the castable on the nozzle as it hangs from the degasser vessel, how many are needed is not known. Too few will not support the weight; too many will only add to the expansion problems already identified. We experimented at the existing number of anchors and at double the anchor spacing (i.e. fewer anchors).

"Drying Cycle" - Both suppliers have indicated a recommended drying cycle for their materials. Occasionally, the scheduling is not adequate and we need to remove a nozzle before it has completed the cool down cycle. Therefore the recommended and abbreviated cycles were examined.

"Curing Temperature" - The temperature at which the castable is allowed to set during the initial stages of curing can determine the final properties of the material.[6] Since the nozzles are typically cured at something close to outdoor temperature, we examined curing temperatures greater than 18°C (65°F) and between -4°C and +4°C (25°F - 40°F).

"Wires Used" - In some applications stainless steel wires are added to castables where cracking can cause premature failure.[7] The wires hold the pieces together rather than having large chunks fall off. Since cracking is a primary mode of premature failure in the degasser nozzles, wires might help. However, exposure to molten steel might melt the fibers. No wires and 1.5% stainless steel wires were set as levels.

"Order of Nozzle" - The degasser vessel refractories last longer than the nozzle refractories. Therefore we exchange nozzles halfway through a bottom campaign. The first nozzle gets the advantage of the preheat that the rest of the vessel receives while waiting to go on-line. The second nozzle is put on cold and receives only a superficial preheat before the first heat of steel is processed. In the past we have seen different levels of performance from first and second nozzles. This may be due to the preheat conditions, product mix considerations or other factors. If this variable turns out to be an important one, further experiments can determine why. The two levels will be the first and second nozzles.

"Dryer Used" - Three ovens are used to dry the cast nozzles. The insulation, burner and control system can be in different states of repair on each. Previous testing indicated that the control thermocouple is not very representative of the temperatures achieved throughout the dryer. Two of the dryers were selected at random to investigate this factor.

"Water Temperature" - The temperature of the mix can affect the rate at which the material sets.[8] It is less effective but more practical to change the temperature of the water than the material in our situation. It is also more representative of how we store the materials. The bags of castable are stored in a heated room. The water pipes are heat traced to keep them from freezing, but temperature can vary. The levels for this experiment were 21°C - 32°C (70°F - 90°F) and less than or equal to 4.4°C (40°F).

Measurement of results

The operating crew at the degasser has agreed to record the nature of the cracking after each heat on the nozzle on a predefined scale of zero to five. They also will record special notes about patching done on the nozzle and other information that might bear on the final analysis.

These records will be reviewed to determine where there appeared to be a natural break in the performance that will allow us to distinguish the performance of one nozzle from the others.

Laboratory Tests

The samples

The samples used for all the tests will be cast from the material mixed for the nozzles themselves. The drying and curing conditions will be the same as the nozzle's as they will be processed at the same time. For each experimental nozzle there will be a set of brick size samples cast.

The tests

Density, porosity, cold modulus of rupture in the as-received state, and hot modulus of rupture will be determined for all samples. Samples from nozzles which did extremely well or extremely poor will be further subjected to hot load deformation and/or slag testing.

In order to measure the effect of the experimental variables on the physical properties of the castables, samples will also be cast under optimum laboratory conditions. These samples will be added to the testing program.

SUMMARY

Once all of the data has been collected. The results of the field work will be analyzed in the manner prescribed by the Taguchi method. The levels for each factor will be compared and the best settings selected for the paper champion. This set-up will then be tested in the field and compared to the predicted performance.

As noted earlier, one factor at a time experiments in the laboratory have been only marginally successful in identifying the properties that are most important to long nozzle life. The trade-offs between various failure modes have made the evaluation too complicated. Once the field results demonstrate what type of material does best overall, the laboratory testing can be used to correlate physical properties of the materials to field performance. This information will then be used to identify new materials that will provide even better results. The field and laboratory results will be presented in future papers.

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[4] Ibid, pg. 123.

[5] Ibid, pp. 73-74.

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[7] Plibrico Japan Company Limited, Technology of Monolithic Refractories, Plibrico Japan Company Limited, (1984) pp. 188-198.

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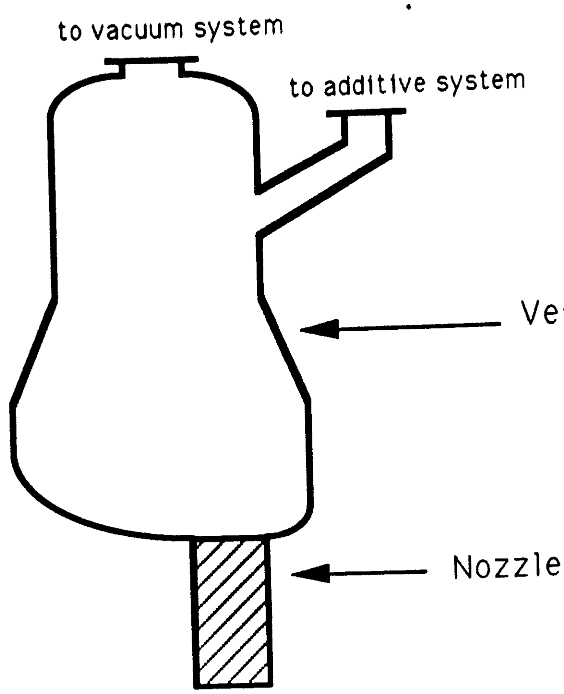

Figure 1 - DH Degasser Vessel

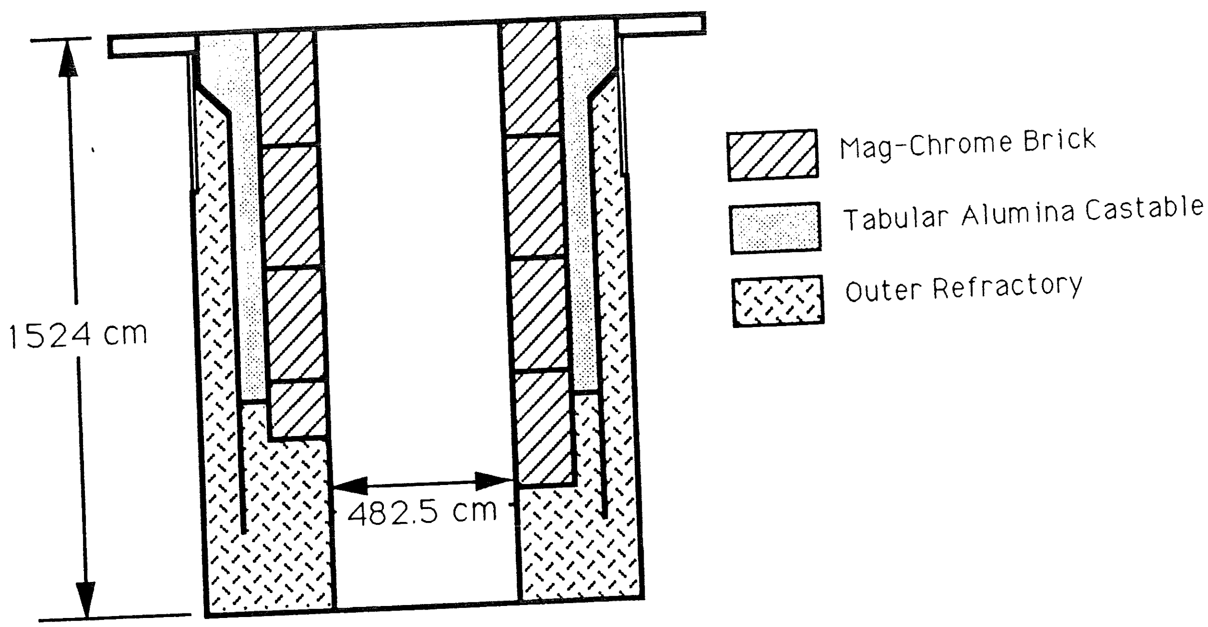

Figure 2 - DH Degasser Nozzle Refractories Cross-section

Table I - Effects of Freezing on Properties of Phos-bonded Plastic

	As Received	Rammed Frozen	Frozen-thawed then Rammed	Rammed then Frozen
Bulk Density (g/cc)	2.95	2.89	2.91	2.92
Apparent Porosity (%)	19.90	22.23	21.47	21.04
Hot Modulus of Rupture (kPa)				
@ 1260°C Avg	7268	7977	8077	7032
Std Dev	813	532	789	225
@ 1480°C Avg	8536	9339	9253	6719
Std Dev	1015	1144	642	447
Hot Load Subsidence @ 1650°C (172 kPa) (Hold 90 min @ temp, total test time 8-1/2 hr)	-13.28%	-15.81%	-14.30%	-15.86%
Slag Test (1650°C/4 hr) (% erosion)	-0.61	-1.54	-3.59	-4.10

Slag Chemistry: CaO - 22% SiO_2 - 54% Al_2O_3 - 6%
MgO - 8%   MnO - 1% Fe_2O_3 - 9%