"SOLVING CORE SHEAR WITH DESIGN OF EXPERIMENTS: -- A CASE STUDY --"

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The foundry had to rework far too many bolt holes. Grinding off a thin cap of metal from the top of each cast bolt hole was only costing the company about 50 cents per hole-- but it was happening almost 100,000 times a year!

M.E. International, located in Duluth, MN, with headquarters in Minneapolis, is a foundry that produces consumable wear parts for the mining industry. Our primary product is mill liners – 500-3,000 lb. alloyed steel castings. Our worldwide customers line their massive crushers and mills with dozens of these castings. From the primary fracturing stages of boulders through the final steps of grinding rock and pulverizing ore, we cast the tools that crush.

Bolt-hole cores that fractured during the casting process were allowing a thin leakage of molten metal to cap over bolt hole openings. A frustrated quality team turned to design of experiments (DOE) -- a statistical method from the 1920s. DOE quickly revealed to us the direction to follow for quality enhancement and cost reductions worth approximately $50,000 a year.

Being a vacuum process facility, we're unique in the manner in which we make mill liners. Our method, commonly called V-Process, surpasses traditional manufacturing methods because of how our molds are held in proper configuration during a pour. Compared with conventional mill liner manufacturing processes, V-Process manufacturing produces cleaner molds, improved surface finishes, and better dimension control. Here's how it's done:

- Pull a thin film of plastic over the shape to be molded.
- Apply a refractory coating over the film.
- Pour sand into a special flask, which has screens and a port.
- Attach a vacuum hose to the port and evacuate air.
- Draw the mold off the pattern.

Our quality team had identified the cause of the skimmed-over bolt holes to be core shear, called “cut-off” or “capped-over” by some. The cause appeared to be what is known as metallostatic pressure. That is, with every cubic foot of molten metal added within a mold cavity, increasing pressure forces a mold up, down, and out. Because of these tremendous pressures, our cores were fracturing at their weakest point – the narrow section within each bolt hole core. Every fracture was inducing a thin, silver-dollar-sized layer of molten metal to flow into the fissure, covering the intended bolt hole opening. Although it took only a moment to power off the skin of metal in our finishing department, those moments were happening 100,000 times per year.

After a variety of futile attempts to halt the hairline fractures, we turned to a DOE software program known as Design-Expert® (Stat-Ease, Inc., Minneapolis, MN). Our hope was to find the ideal combination of casting components that would halt the hairline fractures.

Design of Experiments: A Definition

Design of experiments, abbreviated DOE, provides information about how factors such as time, temperature, or chemistry type will interact in a system. DOE simultaneously evaluates multiple factors within a process, making it a useful tool for foundries. It is superior to traditional one-factor-at-a-time (OFAT) experimentation because OFAT needs many runs to obtain equivalent knowledge of a process. Additionally, OFAT cannot reveal interactions.

Although DOE was invented in the 1920s, it remained unused because it required laborious hand calculations. Today, DOE software easily sets up and analyzes statistically sound DOEs. It does this by fitting data into mathematical equations and predicting outcomes for any combination of values. Consequently, engineers, scientists, and researchers are optimizing responses and discovering winning combinations.

CHOOSE THE FACTORS TO TEST

Our quality team performed three different experiments, each with a different combination of factors. These combinations are shown in Table 1.

	1ST EXPERIMENT	2ND EXPERIMENT	3RD EXPERIMENT
FACTORS TESTED	- Core binder percentage - Vacuum hold time - Sand type	- Core binder type - Vacuum hold time	- Binder system (Confirmation)

TABLE 1. Three different DOE experiments test varying factors that likely contribute to core shear.

The factors were chosen based on our knowledge of the entire process:

- Core binder percentage: (higher binder = higher tensile strength). Chosen to determine whether higher tensile strength reduces core shear.
- Vacuum hold time: Tested to determine whether metallostatic pressure can be controlled further into the solidification process.
- Sand type: Chosen to determine whether more or less silica, for example, improves castings by reacting differently to the mechanisms associated with core shear defects.

DOE OPTIMIZES CASTING METHODS

Once we determined which factors were likely core shear culprits, we established each factor's feasible operating limit for each of the three experiments. That is, each experiment would be conducted at every factor's high and low operating parameters. The high/low parameters we chose are shown in Table 2.

	1ST EXPERIMENT	2ND EXPERIMENT	3RD EXPERIMENT
Factor: **High level:** **Low level:**	Core binder % 3.5 2.5	Core binder type SO2 system CO2 system	Binder System* SO2 vs. CO2
Factor: **High level:** **Low level:**	Vacuum time 20 min. 16 min.	Vacuum time 20 min. 12 min.	
Factor: **High level:** **Low level:**	Sand type 10% silica added 100% Zircon		

*NOTE: The SO2 system provided tensile strength improvements double that of the CO2 system.

TABLE 2. High- and low-factor levels bracket normal operating limits.

DOE methodology eliminates the need to directly test every possible factor combination – thereby saving experimenters time and money. It also finds interactions among factors, something one-factor-at-a-time testing does not. As a part of our experiment, we entered the results, or responses, into the Design-Expert software. The software then fit the response data to mathematical equations that accurately predict what would happen for any given combination – whether the combination had been tested directly or not. Armed with these statistically valid predictive models, the software optimized the key responses and found a winning combination of factors.

Although DOE methods have been in existence for approximately 70 years, they have only begun to be utilized with the advent of desktop PCs. Today, designed experiments courses are being offered increasingly on engineering campuses – far too belatedly, some say. Because DOE is not a college curriculum priority, it is estimated that only 5-10% of engineers currently working know DOE techniques. The engineers and quality professionals at M.E. International were no exception. To gain DOE proficiency, I attended a 3½-day workshop conducted by Stat-Ease, Inc., the creators of Design-Expert software.

Statistical methods taught in the workshop supercede increasingly antiquated one-factor-at-a-time experimentation, known as OFAT. Today, OFAT experimentation requires a great deal more time. And the results are less substantial than DOE solutions.

INTERPRETING THE RESULTS

Figure 1 shows a cube plot displaying three important factors tested in our first DOE. The plot indicates which combination of factors produces optimal process parameters. Zero represents perfectly open bolt holes. Note that the rear, upper left of the cube shows the lowest number on the cube as being 3.0. This extremely favorable condition is achieved with the following combination of factors:

- High core binder percentage
- High vacuum time
- Low sand (no silica added)

Other DOE findings (not shown) also indicate that a strong core is the single most important way to prevent core shear. The time spent holding a vacuum is important, but not as critical as core strength. Experiments 2 and 3 further qualified core strength as the primary factor associated with core shear.

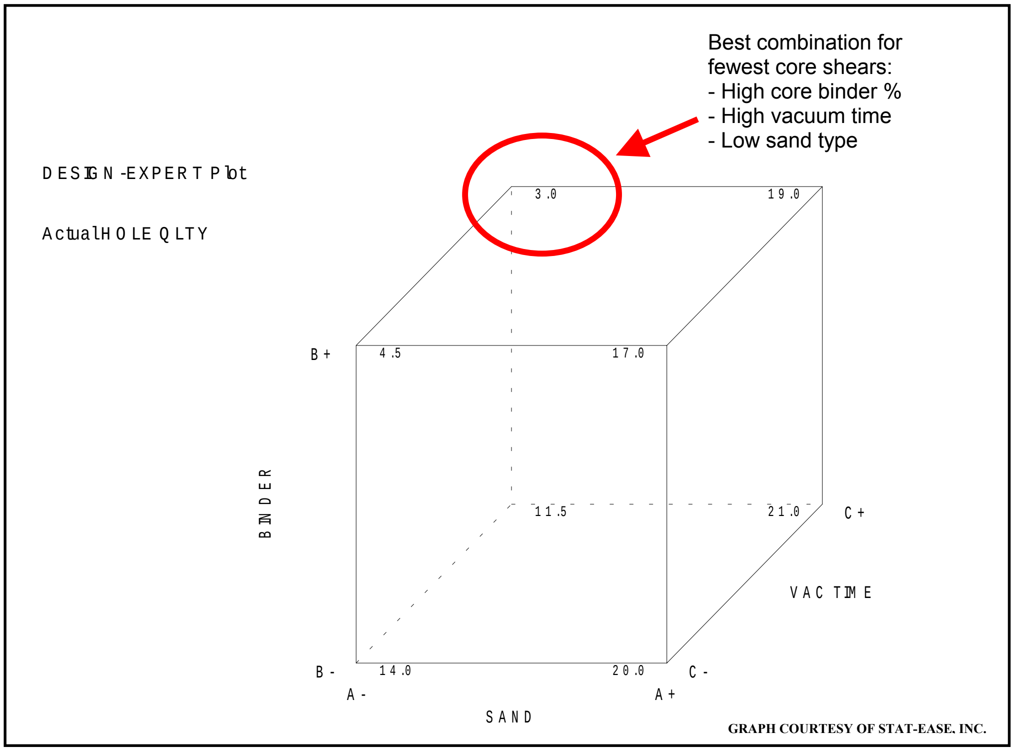

FIGURE 1. A Design-Expert® cube plot reveals the best settings at the back of the cube in the upper left corner. This is where high core binder, high vacuum time, and low sand type A combine to produce the lowest occurrence of core shear.

Further analysis of the results indicated that this combination of factors carried a statistical probability, or confidence, of more than 99.9%. (A probability of 95% or greater is recommended before making critical process changes that would require capital investments.) Confirmation runs (further trials at optimum settings) are also a necessary part of DOE.

During the years that we tolerated core shear, we knew that the skimmed-over bolt holes did not harm the integrity of our liners. But it did mean extra grinding -- 100,000 times a year. Today, our customers continue to receive castings produced via the distinguished V-Process method. And we now know how to produce them just a little faster, one clean bolt hole at a time.

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