Erosion of a sand mold or core can occur when heat from molten metal degrades the binder until the surface can no longer resist the mechanical forces of the flowing metal. Sand can be removed from the surface and carried with the metal stream, resulting in a cavity in the mold/core surface, which forms a corresponding rough protrusion on the casting surface. Depending on the location, the eroded area may or may not cause a problem, but the sand carried with the metal flow will more than likely cause sand inclusions elsewhere in the casting.

To prevent core erosion, foundries must focus on both sides of the equation. If metal velocity, pressure, turbulence and temperature can be reduced, less erosion will result. Conversely, if the mold or core can be made stronger, denser and more temperature resistant, erosion resistance will increase.

Erosion testing has been conducted for a number of years using an “erosion wedge” test casting to evaluate the performance of different sand binder formulations. Typically, these tests are conducted under “standard conditions” where all variables except the test core are held constant. This has resulted in improved binders, but has not put the role of the binder into context with other material or process variables.

A laboratory design of experiments (DOE) was conducted to show the relative strengths of effects of several variables on erosion resistance. This was followed by specific DOEs to improve erosion performance at Waupaca Foundry, Inc., Tell City, Indiana, using its production parameters. This article examines the results.

**Initial DOE**

**Materials and Process Variables**—The erosion wedge test casting has been used in a variety of experiments to evaluate the overall performance of different organic binder systems and sand mixes. It has proved to be a good indicator of field performance of the core material.

An initial DOE was developed to better understand the variables that might affect the results of the erosion test. It was intended to make the test methods more robust to the influences of process variables so that intentional changes would be more clearly represented. It also was de-
signed to compare the relative strength of effects of coremaking vs. process variables.

The DOE variables and levels are shown in Table 1.

**Test Methods**—Core weight and scratch hardness were recorded for each core. The assembled molds were pored with gray cast iron with a carbon equivalent of 4.1%.

The primary output of the DOE was the erosion resistance rating of the 12 wedge castings. The castings were visually rated using a scale of 1 to 5 with 1 as the “best” and 5 as the “worst.” Photographs of the “best” and “worst” castings are shown in Fig. 1.

**Initial Results**—Level average were computed for each variable. An analysis of variation calculation was also performed to show the relative strength of response for each variable (Fig. 2).

The binder % had the greatest effect on erosion resistance with higher binder levels producing less erosion. The sprue height was the next strongest factor with a taller sprue producing more erosion due to higher metal velocity at the point of contact.

The sprue diameter and the metal pouring temperature were the next strongest factors as higher temperatures produced more erosion while the larger sprue produced less erosion. This second occurrence was somewhat unexpected because the larger sprue would allow for faster pouring, higher metal velocities and more turbulent conditions. Why this occurred became clear when the pouring times were compared.

The smaller sprue resulted in a 4-5 sec longer pouring time. The time of exposure of the core-to-metal flow was more important than the flow rate in levels of erosion. The sand type also had an effect as less erosion occurred with a round-grain silica sand.

**In-Plant DOE**

Additional DOEs were conducted to address specific foundry conditions at Waupaca. As part of an ongoing continuous improvement program, it was desired to further investigate the factors most influencing erosion resistance under specific operating conditions.

Cause and effect diagrams were generated to identify the variables and levels were chosen to reflect the extremes of process variation. The four types of sand used within Waupaca were selected as the first variable.

Table 1. Initial DOE Parameters Established for Erosion Test

<table>
<thead>
<tr>
<th>Variables</th>
<th>Level 1</th>
<th>Level 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>PUNB Binder Formulation</td>
<td>X</td>
<td>Y</td>
</tr>
<tr>
<td>Binder Level</td>
<td>1.0%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Sand Type</td>
<td>Silica</td>
<td>Lake</td>
</tr>
<tr>
<td>Pouring Temperature</td>
<td>2750F</td>
<td>2550F</td>
</tr>
<tr>
<td>Sprue Height</td>
<td>16 in.</td>
<td>12 in.</td>
</tr>
<tr>
<td>Pour Weight</td>
<td>75 lb</td>
<td>60 lb</td>
</tr>
<tr>
<td>Spur Diameter</td>
<td>1 in.</td>
<td>0.75 in.</td>
</tr>
<tr>
<td>Coremaking Method</td>
<td>Blown</td>
<td>Hand-Rammed</td>
</tr>
<tr>
<td>Core Humidity Exposure</td>
<td>24 hr @ 50% RH</td>
<td>24 hr @ 90% RH</td>
</tr>
</tbody>
</table>

Four different binders were formulated based on the existing system, but with ester rich (E) and aromatic rich (A) solvent systems and a different isocyanate type used in Part II. Two anti-veining sand additives were selected and compared to no additives. Six other two-level variables were selected to look at the effects of binder Part I/Part II ratio, binder level, mixed sand benchlife, the use of a coating, pouring temperature and casting sprue diameter. The variables and levels are shown in Table 2.

The test castings were pored using ductile iron with selected tests in gray iron for comparison. While the primary interest was erosion resistance, coremaking characteristics also were important. In addition to erosion testing, core weight, core loss on ignition (LOI), the time to core breakdown (BCIRA) and tensile profiles also were tested for each of the 16 mixes to ensure core properties could be maintained.

**Erosion Test Results**—One factor, the use or lack of a coating on the core, accounted for more than 60% of the variation seen within the experiment (Fig. 3). While it is widely known that coatings are effective in reducing erosion, the strong effect somewhat overwhelmed the influence of other factors.

Sand type, binder type, the anti-veining additives and the binder % all showed some effects. Selected tests confirmed that erosion results were slightly more severe with ductile iron than gray iron under the same conditions, but the variation from test to test was less than expected.

**Core Test Results**—Supplementary testing of core weight, core LOI, BCIRA and tensile profiles showed the effects of different variables. The core weight was most strongly affected by the binder percentage and sand type with minor contributions by benchlife.

Sand 1, a four-screen silica sand, produced the highest weight cores. The lower binder level and the fresh mix benchlife also increased weight. Core LOI was a function of binder level. BCIRA at both 1 hr and 24 hr core age was most strongly affected by sand, binder type and binder percentage.

Sand 1 also produced the longest breakdowns. The ester rich solvent package and higher binder percentages also increased breakdown time. Tensile strengths were overwhelmingly affected by binder percentage with modest contributions by sand type, anti-veining and binder type. As expected, higher binder levels produced higher tensile strengths.

Sand type also had a strong influence. The use of fine sand additives had a slight negative effect on core strength. The % contributions for the variables for each of the tests are shown in Table 3.

Before testing began, the goal was to illustrate a correlation between the physical properties of the core (as measured by core weight, LOI, BCIRA and tensile strength) and erosion test results. If a correlation was seen, this would indicate that...
core tests could be used as a predictive tool for erosion. This would allow for the control of erosion through offline testing. However, the overwhelming effects of the coating in these trials masked these relationships.

## Follow-up DOE

A follow-up DOE was designed to study the influence of more specific process variables. These included sand grain fineness number (GFN) and screen distribution for a specific sand type, sand temperature at time of mixing, mix benchlife over a wider range and further variations in the boiling point of the binder solvent package. Ductile iron erosion test castings were used and core weight and core tensile strengths were measured for each of the nine trials.

### Test Results

Even with the range of variables used, little variation was present between test castings. This was unexpected because core tensile strengths showed significant differences from those of bare cores. It was evident that the variables affected core blowing properties but did not impact the erosion test cores. This led to the development of a new test casting configuration.

### Test Method Redesign

It was believed that the large chunky erosion wedge core might not illustrate the influences of the variables under study. As a result, a smaller, thinner core was used, as it is more sensitive to coremaking and process variables. Half-inch cores were blown under the DOE conditions and later inserted into a STD erosion wedge mold package. These cores were again poured and castings evaluated as with the previous tests.

### Redesign Test Results

The erosion wedge castings with the modified erosion wedge cores exhibited greater variation in erosion severity. The benchlife of the sand mix when the cores were made had the strongest effect with increased benchlife reducing erosion resistance. Sand GFN showed a nonlinear effect with the best erosion resistance from the 55 GFN sand with an increased percentage on the 140 screen. Sand temperature at 110°F and 70°F exhibited less erosion than the 55F sand. This is consistent with tensile strength development. The binder solvent package still showed only minor effects.

### Results Correlating to Production

So what do these tests mean to a foundry's production and casting quality? Following are some conclusions drawn from the experiments:

- The most effective means of controlling erosion over a wide range of phenolic urethane coldbox binder compositions, sand types and process variables is a properly chosen and applied refractory coating.
- Sand type, grain fineness number and screen distribution have a significant affect on both erosion and core properties with finer sand, generally reducing core strength.
- Binder level and binder compositions are the controlling factors for core properties and are significant factors in reducing erosion.
- Large variations in pouring temperature and time showed a strong effect, but smaller variations (as might be controlled within a normal foundry operating range) were less important.
- Sand additives, while potentially valuable for other reasons, had a moderately negative affect on erosion.
- The composition of the solvent package of the binder systems had only a weak affect on erosion but strongly impacted coremaking properties.
- Certain types of variables that affect core blowing characteristics were not shown to be important using the standard erosion test. However, a more sensitive test showed the importance of sand mix benchlife, sand GFN, and sand temperature.

This article was adapted from paper 403-114-3068-2003 AFS Transactions.

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### For More Information
