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# Adapting Hot Distortion Curves to Process Control

## Using new hardware and software, hot distortion tests can help foundries reduce process variation and improve casting quality

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The hot distortion test measures the distortion behavior of chemically bonded sands when exposed to heat, providing a model for understanding how chemically bonded molds or cores will react when subjected to molten metal. Using hot distortion curves enable foundries to reduce process variation and improve casting quality.

In the hot distortion test method, a cured sand specimen is preferentially heated on one side, and the millimeters deflection of that specimen is measured over time and recorded as a curve. The experimental setup for a hot distortion test is shown in Fig. 1. In theory, this setup is similar to a mold or core section that comes in contact with molten metal.

The data curve from this test is shown in Fig. 2. A typical hot distortion curve from a shell bonded core or molding sand is comprised of four basic regions:
- Region 1—Upward Deflection

This portion of the curve is determined primarily by the base sand and results from the preferential expansion of sand on the side of the specimen facing the heat source. As the sand on the heated side expands at a rate greater than the sand on the opposite side, the probe is pushed upward, and the sand expansion is measured as a positive number by the hot distortion tester.

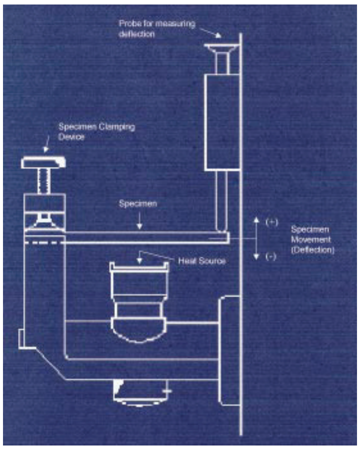

Fig. 1

The type, shape, size, distribution, and compacted density of the sand may influence this region of the hot distortion curve (HDC). Reducing upward deflection to a minimum positively affects the casting process.
- Region 2—Thermoplastic Relaxation (Plasticity)

The base sand and the properties of the chemical binder determine the thermoplastic region. It is common for polymers, in this case a chemical binder, to go through thermoplastic relaxation before binder curing becomes the dominant distortion mechanism. In the case of shell sand, initial heating of the test specimen begins to melt the shell resin, causing the viscosity of the resin to drop. At this point hexa-methylenetetramine, mixed into the phenolic resin during the sand coating process, begins to decompose into ammonia and formaldehyde. The sand specimen sags as the binder flows and bridges between sand grains. In turn, the probe moves downward and this relaxation is measured as a negative number by the hot distortion tester.

Although it is counterintuitive to think of cured sand as having plasticity, some degree will generally be observed. Controlled plasticity helps avoid casting problems such as hot cracking and veining.

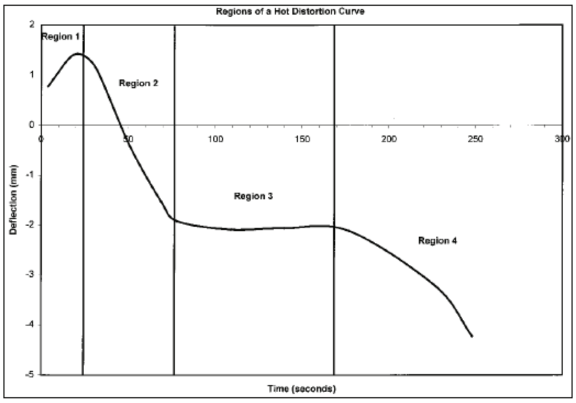

Fig. 2

| Region 1<br>Upward Deflection | Region 2<br>Thermoplastic Relaxation | Region 3<br>Thermosetting | Region 4<br>Degradation and Failure |
|---|---|---|---|
| Base Sand Distribution | Binder Type | Cure Rate | Specimen Density |
| Base Sand Type | Degree of Cure | Degree of Cure | Core Shakeout |
| Base Sand Shape | Dimensional Stability | Binder Type | Resin Content |
| Specimen Density | Tendency Toward Veining or Thermal Cracking | Hexa Content | Hot Strength |

Table 1

It is somewhat of a misnomer to refer to chemically bonded sand as 'cured' when in reality it is only partially cured. Once the resin of a mold or core has been fully cured at the expense of plasticity, the resin bonds will immediately break down when exposed to casting heat. Fully cured cores and molds tend to be brittle, react poorly to thermal shock, aggravate metal penetration, and often break down too quickly during casting.

Excess plasticity can also be undesirable. If a core or mold relaxes too much during casting, the final casting may fall outside the range of acceptable dimensional tolerance.

- Region 3—Thermosetting

Thermosetting is associated with the curing of the chemical binder by heat. In the case of sand bonded by shell resins, formaldehyde released from the decomposing hexamethylenetetramine is consumed by the phenolic resin, marking the change from a thermoplastic to a thermosetting resin.

The additional crosslinking of the binder becomes the mechanism which dominates the thermosetting region of the HDC. This reaction occurs at the expense of thermoplasticity.

As the thermosetting reaction proceeds through the specimen, a corresponding change in the slope of the HDC is observed. The slope becomes less negative compared to the slope recorded in the thermoplastic region.

- Region 4—Degradation and Failure

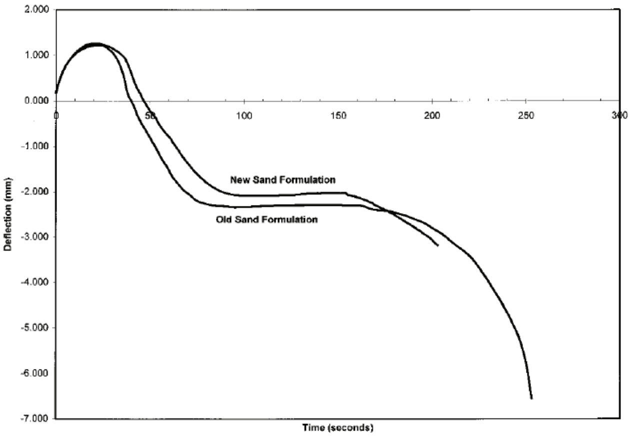

Fig. 3

After continued heat exposure during casting or hot distortion testing, the chemical binder will burn and the chemically bonded sand specimen, core, or mold will break down. This is the dominant mechanism in the degradation stage, which ends with the sand specimen's mechanical failure.

The length of time, as measured in seconds, from initial specimen heating to mechanical failure (i.e., time to failure) is described as a chemical binder's hot strength. HDCs that prematurely fail are indicative of specimens lacking hot strength that could result in core and mold breakage. However, a lower hot strength may result in increased sand removal at shakeout prior to blast cleaning.

An increase in time to mechanical failure represents sand specimens with high hot strengths that can result in casting production problems associated with sand having poor collapsibility characteristics. A core or mold that remains rigid after the metal has solidified around it may cause hot tears, cracks, or a stressed condition in the finished casting.

The four regions of the HDC can give metalcasters insights into many properties important in making good chemically bonded molds and cores and, more importantly, quality finished castings. The brilliance of the HDC is its unique ability to describe in detail to a trained metalcaster a variety of extremely important characteristics required to make a quality casting. Table 1 illustrates some of the properties of cores and molds that may be reflected in the shape of the HDC.

### A Case Study in Using Hot Distortion Curves

Proper analysis of an HDC can provide detailed insight into the process that can be achieved by no other standard sand test.

For example, a shell sand foundry utilizing HDCs was able to easily determine unique characteristics of a newly formulated base sand compared to its original base sand. HDCs from both the new sand and standard production sand are displayed in Fig. 3. All conventional sand tests for the two samples yielded similar results. These tests included grain fineness and distribution, hot shell tensile strength, low level optical microscopy, loss on ignition, clay content, melt point, and moisture. On the basis of this testing, the foundry would have anticipated no difference in performance between the shell sands. Only by using a hot distortion test did the foundry predict some differences in performance, further verified in production.

First, the foundry predicted a difference in the plasticity of the molds and cores judging from the dissimilarity of the HDCs demonstrated in Region 2, as shown in Fig. 3. This was verified in production by the tendency of molds to thermal crack.

More notably, the foundry predicted that castings would clean more thoroughly in shakeout because of the reduced time to failure, as measured by the new sand formulation's HDC. In production, this attribute appeared as a reduction in the amount of core sand left in castings after shakeout but before blast cleaning.

**Determining the Optimum Curve**

What does a good curve look like? Most often this is answered by observing the performance of the chemically bonded molds or cores in actual foundry operation and the quality of the finished casting. Foundries satisfied with the performance of their chemically bonded sands, may obtain a normal curve and call it a standard. Foundries that want different properties from their chemically bonded sand systems may wish to see specific changes from the shape of their normal HDC.

Because the hot distortion test provides a curve and not an individual numerical reading, it is not easy to quantitatively determine what a normal curve looks like without numerous mathematical calculations. Also, the hot distortion test equipment, traditionally available to foundries, has not provided a quantitative method to determine if a curve is normal.

The HDC can be an extremely useful quality control tool in foundries utilizing chemical binder systems and/or commercial coating facilities. However, previous attempts to utilize the curve have been geared more towards qualitative and research purposes. The conclusions drawn from resulting curves were generally considered speculative at best. Due to the difficulty of differentiating subtle changes in curve slopes, valleys, and peaks, only qualified research and/or production management personnel have the knowledge to interpret and compare curves. The use of the HDC as a production control tool has been limited.

This stems from the type of data output delivered from older generation hot distortion instruments, represented by a qualitative curve without any easily defined numerical values of magnitude. Interpreting and/or fitting a complex HDC was a time consuming task requiring complex mathematical functions. Determining normality and acceptable process variation has not been investigated until now.

Determining variation of a discrete characteristic and/or region of an HDC considered typical versus the degree of variation considered excessive for a particular process has not been studied. The ability to differentiate excessive variation in an HDC from normal process and raw material variation would elevate the hot distortion instrument from the ranks of a research device to a true quality control tool.

With this in mind, the partnership of Simpson Technologies Corp. and Ing. Ricardo Gerosa SRL, with input from Grede Foundries Inc., has developed a new hot distortion instrument and software to provide a simple method of determining what a normal HDC looks like for any chemically bonded sand system (see Fig. 4). This integrated system can provide a tool to allow each individual foundry, binder supplier, or commercial shell sand producer to quickly and easily determine normal hot distortion characteristics of their specific chemical binders and chemically bonded sand systems.


Fig. 4

**A Method for Determining a Normal Curve**

Statistically speaking, one important characteristic of normal behavior is that an average and a standard deviation can describe it.

For a measurement in which a single reading is obtained, defining normal behavior is relatively simple. To define the normal compactability of a green sand system, for example, you can run compactability tests on a large number of sand samples from the population—i.e. sand system. After testing, compute an average compactability number and calculate the standard deviation between tested compactability numbers. In this case, a compactability number can be considered normal if it fell within the range of the average compactability, plus or minus three standard deviations.

Similarly, the normal behavior of an HDC can be determined if the curve is broken down into its individual measurements of deflection per unit of time measured in seconds. A computerized hot distortion instrument gives metalcasters a system that will overcome the tremendous burden of these calculations. The hot distortion instrument shown in Fig. 4 is a computer based digital system, the optimum type of system for determining a normal HDC.

First, the computer based tester automatically stores distortion data as a series of individual digital measurements of deflection. Secondly, the instrument can export these digital data to powerful data analysis software programs, such as spreadsheets. Once these data are in a spreadsheet, the software can perform hundreds of calculations necessary to quantitatively compute and compare multiple HDCs.

Deflection and time data can be easily manipulated within a spreadsheet to determine simple descriptive statistics including

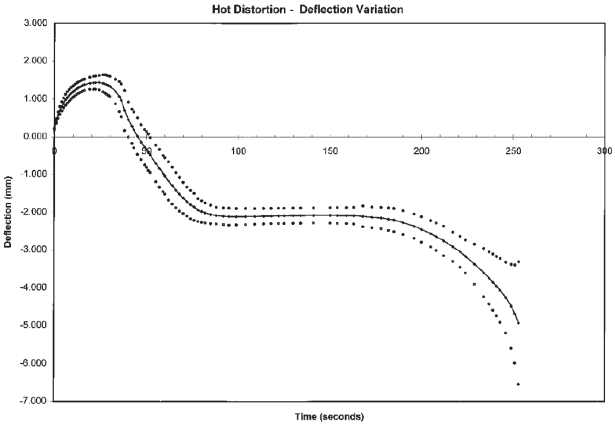

Fig. 5

averages and standard deviations on deflection data at one second intervals throughout the HDC. Each deflection point for every one second interval from hundreds of HDCs may be included to determine normality at any given point in a complex curve.

From this information, an average curve can be easily plotted within the spreadsheet software. Using the calculated standard deviation at each one second interval, a standard process variability can be calculated. This variability is a natural part of the HDC and can be attributed to variations in process, raw materials, test specimens, instrumentation, and operator error. Establishing a plus or minus three standard deviation tolerance of a curve allows metalcasters to distinguish between expected curve variation, called common cause variations, and unusual fluctuations, known as special cause variations. A special cause variation may require immediate corrective action, whereas a common cause variation may be ignored.

After calculating plus or minus three sigma upper and lower control points for each deflection point, control limit curves can be reintroduced to the computerized hot distortion tester, which receives the data and stores and displays them as upper and lower control limits on a color monitor while production tests are being performed (see Fig. 5). The HDCs can be stored for a variety of binder formulations.

Since a tolerance band between the upper and lower control curves is displayed during a standard production test, interpretation of a normal curve does not require the guidance of a trained expert. An operator can quickly and easily determine if the test curve intersects the tolerance limits at any point on the curve. An intersection of curves visually depicts a process or raw material that has drifted out of control and may require immediate attention (see Fig. 6).

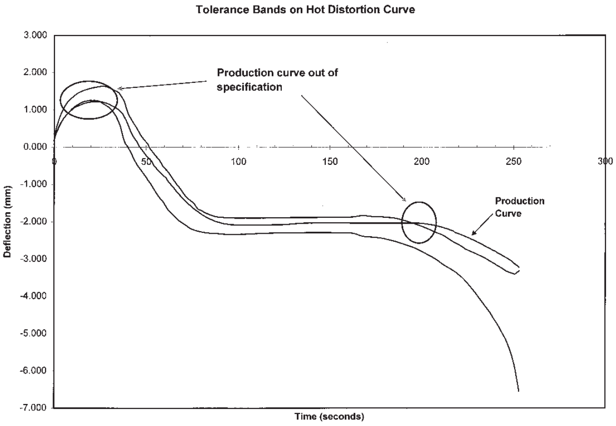

Fig. 6

## Statistical Process Control Charting for Hot Distortion Testing

The ability of the new hot distortion instrument and software to easily generate numbers of varying magnitude allows metalcasters to generate and utilize statistical process control charting techniques to further analyze an HDC.

Process control charts plot data in time sequential order from left to right. These charts include three lines that represent the process mean and upper and lower control limits calculated from the process variation. Using statistical process control charting techniques, important characteristics of a curve can be defined and plotted.

Incorporating this technique into standard hot distortion testing gives metalcasters or binder producers a greater detailed picture of the process. As deflection data are introduced onto a chart, they will fall randomly within the calculated control limits without displaying any particular pattern or trend, and the process/raw materials would be considered in statistical control. However, if a deflection point falls outside either the upper or lower control limits and/or exhibits a nonrandom pattern or trend, the process may be out of control. This may occur even if the entire HDC is well within the upper and lower tolerance limits displayed on the instrument's monitor. Any nonrandom event could be the sign of unwanted process variation or, conversely, the same pattern or trend could be favorable and should be studied to determine its cause. This information may be used to permanently improve the process and/or raw materials resulting in improved casting quality and lower variation. A typical x bar-R chart from a series of HDCs is shown in Fig. 7.

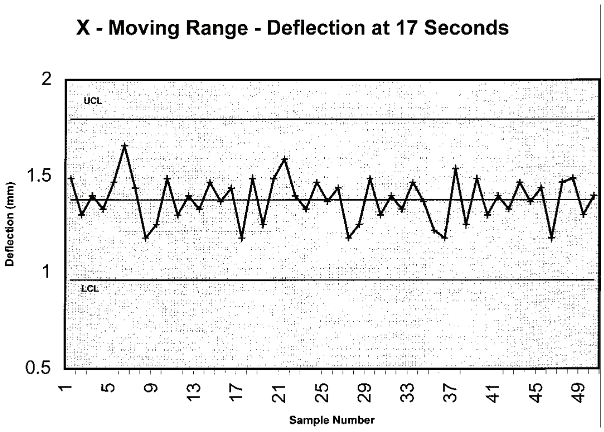

Fig. 7

### Hot Distortion Curves and Process Capability Studies

By using the new instrumentation and software, a further detailed analysis of critical aspects of an HDC could include process capability studies. Once these critical aspects are in control, a standard process capability study could determine if the process and/or raw materials are capable of meeting engineering specifications.

An increased awareness in reducing common cause variation is required to improve the process capability of a critical aspect of an HDC. A complete understanding of the underlying sources within the process that reflect variation, such as mixing performance and consistency of raw materials, is required to reduce process specifications. If process improvements have been made, then the new hot distortion software enables metalcasters to carefully monitor the results of the change and verify the effectiveness of the action.

### Conclusion

Adapting new software and hardware solutions to a standard hot distortion test provides an effective new process control tool to metalcasters, allowing a simple method of determining what a normal hot distortion curve looks like for any chemically bonded sand system. The use of a statistically derived tolerance band between the upper and lower control curves gives an easy interpretation of production curves without the guidance of a trained expert. The incorporation of standard control techniques may also be utilized in parallel with the hot distortion tester to help tighten process control. Hot distortion tolerance bands will enable a foundry to reduce process variation and improve casting quality.