

Thermal Distortion Testing at Ferrous Superheat Temperatures

S.N. Ramrattan, R.A. Makin, Z. Tay, & S. Phalke

Western Michigan University, College of Engineering and Applied Sciences
Kalamazoo, Michigan, USA

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ABSTRACT

As the ever growing need to produce complex castings increases, so does the complexity of cores and molds. In order to accomplish near-net-shape casting with minimal defects, it is necessary to understand the thermal-mechanical effect suffered by the cores and molds when different binders, additives and coating are used for precision sands at the superheat temperature for an alloy.

Thermal distortion is an American Foundry Society (AFS) standardized test (#AFS3350-18-S) for chemically bonded sands. The device can accommodate an AFS standard 50 mm disc-shaped specimen that is 8 mm thick. The specimen is automatically brought into direct symmetrical contact with a hot surface. The machine applies a ramping force to the specimen which represents a hydrostatic head pressure experienced by a core and mold wall during filling with cast alloys. Further, the machine maintains a constant force signifying a filled mold through casting solidification. During this time the instrumentation is designed to capture temperature from the specimen and both longitudinal (axial) and radial movement in the specimen. Until now the maximum test temperature was 1000C (1832F) which underestimates a ferrous superheat temperature. In this study, results show interesting graphical representations of the amplified thermal-mechanical distortions in various polyurethane cold-box sand systems at cast iron interfacial superheat temperatures. Most conspicuous was the augmented pyrolysis and sand loss occurring at the hot-surface specimen interface.

Keywords: chemically bonded sand, Foundry 4.0, precision sand, penetration, thermal distortion, superheat, veining

INTRODUCTION

Precision sand molds and cores using chemical binders are the primary technology for the production of US automotive powertrains and certain aerospace components.¹⁻³ Problems with the sand casting process arise from variation. This can come from many sources

such as grain size, grain shape, chemical composition, additives, and metallostatic pressure. Thus, sand has many potential sources of variation; but it is still subject to the pressures of delivering near-net shaped castings. Understanding those variations is a key issue for achieving good process control an important requirement in Foundry 4.0.

Sand's versatility and ease of use foster rapid innovation in an industry where the ability to change quickly can mean survival. This is especially true with the development of chemically bonded sand systems. Unfortunately, the binder system is also a significant source of variation. The concentration of binder in the sand, and the mix of the binder constituents can all have significant effects on the final castings. Additionally, new binders are constantly being developed in response to various environmental and product quality concerns, thus creating new potential sources of variation.

Chemically bonded sand molding technology remains an important part of metalcasting technology because it permits precision sand castings. Chemically bonded sands used with cores and molds are conventionally processed by techniques such as hot box, nobake, cold box, and 3D print additive manufacturing. As sand composites (mold and core media) come into contact with elevated temperatures, a thermal gradient will develop unique to that particular composite. When a sand composite comes in contact with elevated temperature, the heat transferred causes thermo-mechanical movement and thermo-chemical reactions that result in dimensional changes at the mold-metal interface. At any given temperature these dimensional changes or thermal distortions are attributable to simultaneous changes in both the sand and the binder. Depending on the type of binder used and the temperature at any point in the sand plane, thermally induced reactions occur simultaneously along with sand expansion leading to significant distortions in the composite shape.²

A disc-shaped specimen has been used in the foundry industry as a supplementary mechanical test specimen for chemically bonded sands.¹⁻⁵ The disc-shaped specimen (50 mm dia., 8 mm thick) is a standardized test specimen of the American Foundry Society (AFS).⁴ An AFS standardized thermal distortion test (TDT) for chemically

bonded sands employs the same simple geometry for a specimen.¹⁻⁵

THERMAL DISTORTION TESTING (TDT)

The thermal distortion tester (TDT) uses disc-shaped specimens to compare chemically bonded sand systems. A sand composite is brought into direct symmetrical contact with a hot surface under pressure. The test temperature is variable and can be set to represent molten metal temperatures for the specific alloy for which the core/mold material will be used such as aluminum 760C (1400F), copper-based alloys 1204C (2200F), cast iron 1400C (2552F), and steel 1600C (2912F).

The TDT had a limitation as a laboratory test device. Heretofore, the maximum test temperature using resistive heating was 1000C (1832F).¹⁻⁵ An aim of this investigation was to improve upon the existing heating technology of the hot surface so as to provide meaningful practical information to practitioners and researchers. Therefore, the intent of this study is to develop and evaluate a clean heating and control technology for the TDT. Achieving an actual ferrous alloy superheat temperature against a chemically bonded disc-shaped specimen will provide more meaningful data.

The TDT also has the capability to reproduce the pressures that sand binder systems, will experience from molten metal filling and solidification in a mold. The duration of the test is set to mimic the time it takes for the metal skin to form at the mold wall interface. After thermal exposure, the test specimen is still intact allowing determination of additional valuable information that can be gained after thermal exposure, including the strength, a visual analysis for cracks (which, in the metalcasting process, could result in penetration and/or veining), and a weight loss measurement that relates to pyrolysis of binder bridges and the amount of loose, unbonded sand generated at the mold metal interface as a result.^{3,5} The TDT was designed with the intent of obtaining deformation data for any sand binder system (natural or synthetic).

The TDT has the capability to represent the heat and pressures that sand binder systems, will experience from molten metal filling and solidifying in a mold. The word “represent” must be emphasized since molten metal has never been used with the TDT, and there is no exact simulation of casting condition during the test.

Operating conditions of the TDT device are like those where a mass of molten metal is pressing against the mold wall in a pseudo-static state. The load (metallostatic head pressure) on the specimen is held constant, and the specimen can only move into or out of the face of the hot surface depending on whether the specimen is expanding or plastically deforming (Figure 1). Holding the

temperature of the hot surface constant during testing simulates the mass of molten metal.

All of the functionality of the device is accomplished through the use of several instruments, controllers, heating system, mechanical devices, and a computer that is used to record data. The description of these features follows.

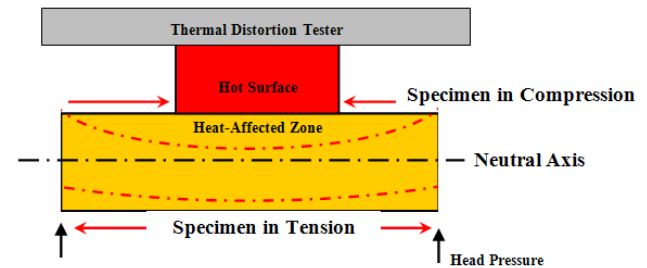


Figure 1. Thermal Distortion Test (TDT) stresses on the specimen are shown.

Load Calculations

A disc-shaped specimen receives a load about the circumference of one side as the other side is pressed onto a heated metal surface (1 mm support about the periphery of the specimen). Dividing this total load by the area of the heated surface approximates pressure. Thus, varying the load emulates a metallostatic pressure while controlling the metal surface temperature.^{1,3,5}

Loading Mechanism

The loading mechanism allows for the approximation of metallostatic pressures during the mold filling and solidification of a casting. For better control and quantification of the resulting distortion, a uniaxial pressure load needs to be applied. This is accomplished by a free floating linear bearing slide that is coupled with an electronic actuator to provide the movement. The slide ensures that center axis of the specimen comes into contact with the center axis of the heated surface. The specimen is loaded into a ceramic tray. The tray locates the specimen against two pins. In addition, the tray is recessed so that any thermal-mechanical movement that takes places will not be restricted. It also allows the specimen to be pressed against the hot surface.

To prevent any shear forces from acting on the specimen surface in contact with the heater, a two-axis gimbal was used. The gimbal used three separate rings, one ring was fixed to the linear slider while the remaining two rings were allowed to rotate on two axes, each of which was 90 degrees from each other and oriented 90 degrees to the heated surface axis (Fig. 2).

The axes for this gimbal system are centered at the face of the specimen. This prevents scuffing that might occur

when the specimen experienced uneven distortion since a static fluid would not create a shear load on a mold wall.

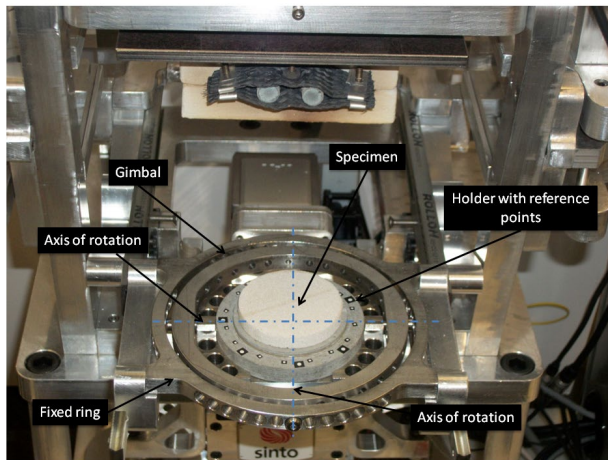


Figure 2. The 2-axis gimbal test assembly.

Molybdenum Disilicide Heating System for Hot Surface

The previous iteration of the TDT machine had the capability of achieving hot surface temperatures of 1000C (1832F) using a silicon carbide heater.¹⁻⁵ The hot surface is a hollowed-out conical frustum, with a tip radius of 20 mm, made of MAR247. MAR247 is a high-performance nickel-based superalloy that was developed specifically for use in high-temperature aerospace applications. The alloy is known for its excellent mechanical properties at high temperatures. The superalloy is commonly used in the production of turbine blades, vanes, and other components in aircraft engines.

Modifications were made to the TDT machine in order to achieve greater heating potential while using an environmentally friendly heat source. A molybdenum disilicide (MoSi_2) heater was selected to replace the silicon carbide heater, due to its higher upper operating temperature limit of 1800C (3272F). The hot surface material was changed to a high-purity (99.95%) tungsten, which can withstand pressures that are required during the test at the new elevated temperature. The shape remained the same as the initial design.

The MoSi_2 heater is mounted horizontally inside a fused silica insulation housing along with the new tungsten hot surface and thermocouple. The fused silica housing has a service temperature of 2000C (3632F) and to enhance refractoriness, the housing was coated with zirconia.

Instrumentation

The TDT uses a variety of sensor devices to collect data and control the heating process. The data that is acquired during each test is radial and longitudinal (axial) deflection, temperature at the hot surface and backside of specimen, and time. Longitudinal deflection in the specimen is tracked using a real time feedback loop

within a commercial controller. The controller software uses the load as a reference and maintains the set value by changing the position of the actuator. To track radial movement, the TDT uses a green light camera system. This system uses the green light to create a shadow of the specimen so that the read-head can measure specimen diameter. The temperature of the hot surface is sensed by a R-type thermocouple. To measure the temperature on the backside of the specimen, a non-contact infrared device was used. Time is recorded based on the sampling rate of the data acquisition system. All the temperature and movement signals are fed back to a data acquisition system that is attached to a personal computer (PC). Data is analyzed, stored, and displayed for each test.

Safety

Special attention was given to safety. The TDT is simple to operate and human interaction is done away from the hot surface. This is possible with the use of two horizontal slides that support the gimbal assembly. This allows users to stay much farther away from the hot surface which can be as hot as 1400C (2552F). Once the specimen is located in position, the automatic test may start/stop with the click of a mouse.

OBJECTIVE

The purpose of this project was to test and compare two round grain silica sand binder systems at ferrous superheat temperatures 1400C (2552F) using the TDT. The elevated test temperature will provide fresh data and results for foundry engineers and researchers.

METHODOLOGY

The testing procedure consisted of three major steps: 1) preparation of disc-shaped specimens, 2) TDT testing and 3) observation of physical and mass changes. To ensure that the study was executed methodically, an experimental design of two binder levels at two elevated temperatures was employed.

Note: All specimens were prepared and tested in laboratory conditions. Ambient conditions were controlled: temperature at $20 \pm 1^\circ\text{C}$ ($68 \pm 1.8^\circ\text{F}$) and relative humidity at $50 \pm 2\%$.

1. PREPARATION OF PUCB SPECIMENS

The sand used in this study were the same size and distribution (Table 1). The same type of chemical binder was used to bond grains into test specimens but the amount was varied. AFS standard disc-shaped specimens (cookie cores) were fabricated to 50 mm in diameter with 8 mm section thickness. Polyurethane cold box (PUCB) specimens were prepared using washed and dried round grain silica sand (Table 1).

Table 1. Properties of PUCB Sand

Source	AFS/gfn	Shape	% PUCB Resin	Roundness/ Sphericity (Krumbein) ⁶	pH	Acid demand (pH-7)
Illinois	59-65	Round	0.9 or 1.4	0.8/0.8	7.1	0.8

The PUCB disc-specimens were prepared by blowing the specimens with a laboratory core blower into a four-cavity disc core box (Fig. 3). Each cavity had its own gate opening and a vent opposite the gate.

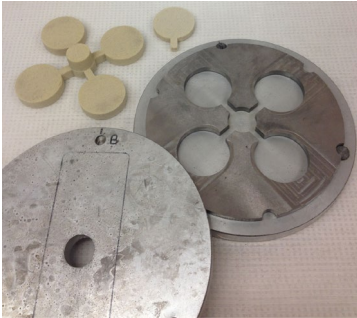


Figure 3. The four-cavity disc core box and disc-shaped specimens.

Materials

Silica sand (Table 1), PUCB binder system Part 1 and Part 2 (mixture ratio 55 Part 1: 45 Part 2)

Equipment

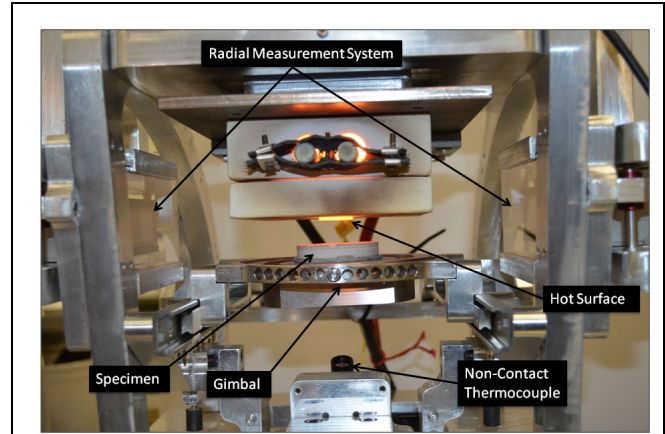
DeLonghi mixer, core box, core blower.

Procedure

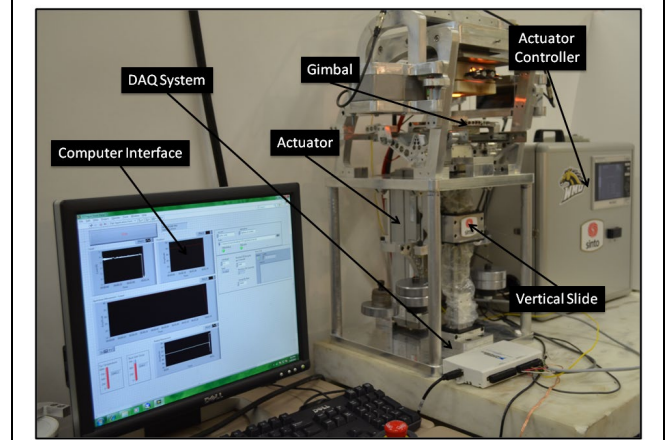
1. Add weighed sample of sand to DeLonghi Mixer.
2. Make two pockets in the sand.
3. Add Part 1 component into one pocket and Part II to the other pocket.
4. Mix for 1 minute.
5. “Flip” mixture and mix for 1 additional minute.
6. Using laboratory core blower set at 0.379 MPa (55 psi) for 0.5 second blow the mixed sand into the four cavities of the core box (Fig. 3).
7. Cure by gassing with TEA using a Luber gas generator. Gassing parameters: 1 sec gassing with TEA, followed by an air purge for 6 seconds (gas pressure was 0.172 MPa (25 psi) and air purge pressure was 0.103 MPa (15 psi)).

2. THERMAL DISTORTION TEST (TDT) TDT Procedure

The TDT test procedure (AFS 3350-18-S) is documented in the “AFS Mold and Core Test Handbook.”⁴ To operate the TDT (Fig. 4a and 4b), the electrical power was switched on and the temperature control was adjusted to represent a specific temperature. In this experiment the test temperatures were 1000C (1832F) and 1400C (2552F) representing low to high cast iron/sand mold interfacial temperatures.



4a. Close-up view of testing apparatus



4b. Overall machine setup

Figure 4. The Thermal Distortion Test (TDT) machine test setup.

The predetermined load on the actuator of the TDT can be programmed to a specified force simulating molten metal acting on a core or mold wall (head pressure). A 20 cm (8 in) head height for cast iron with a density of 0.69 g/cm³ (0.25 lb/in³) provides a head pressure of 0.016 MPa (2.50 psi) (Head Height * Metal Density). The load (force) used during the TDT was 4.50 N (1.01 lbf), and was calculated to represent a 20 cm (8 in) cast iron head height (Contact Area of TDT Hot Surface * Head Pressure). This particular head height was used to represent a head pressure typical of medium-size iron castings.

The computer and data acquisition system was switched on for controlling, monitoring and plotting graphs of temperature/time versus distortion. The temperature was controlled using a R-type thermocouple at the hot surface and a non-contact digital infrared temperature sensor monitored temperature at the back of the test specimen. The temperature monitoring instruments allowed a thermal gradient to be calculated across the thickness of the disc-shaped specimens.

The test specimen was inserted into a ceramic tray that was placed into a pivoting holder (gimbal). The test specimen was then automatically raised until direct symmetrical contact was made with the 2.00 cm dia. hot surface. This simultaneously engaged the actuator and a high speed laser micrometer scanning sensor that measured the distortion longitudinally and radially. The data acquisition system automatically logged and plotted the distortion/temperature versus time curves. The duration of the TDT was 90 seconds (specified by the AFS MMIR Steering Committee); however, this could be varied.¹⁻⁵ During the test, the programmed force was set to represent the force of molten metal pressing against the mold/core wall. The force loads the circumference of the bottom of the specimen, which presses the top of the specimen against the 2 cm dia. hot surface. Any downward movement of the gimbal is recorded as expansion (and appears as upward movement when plotted). Any upward movement of the gimbal, due to the specimen becoming plastic and distorting is recorded as plastic deformation (and appears as downward movement when plotted).

Measure of Thermal Distortion

The measurement of thermal distortion using the thermal distortion curve (TDC) has been somewhat complicated and confusing. In this section the authors will present a straight forward approach to the measurement of thermal distortion. Until now, longitudinal distortion (D_L) and radial distortion (D_R) were represented by absolute values of the TDC as displayed in Fig. 5. This figure shows a curve for “System P” where D_L is represented as (A). It also shows “System Q” where D_L is represented as (X + Y + Z). Similarly, Fig. 6 shows a curve for “System P” where D_R is represented as (B). It also shows “System Q” where D_R is represented as (C + D + E).

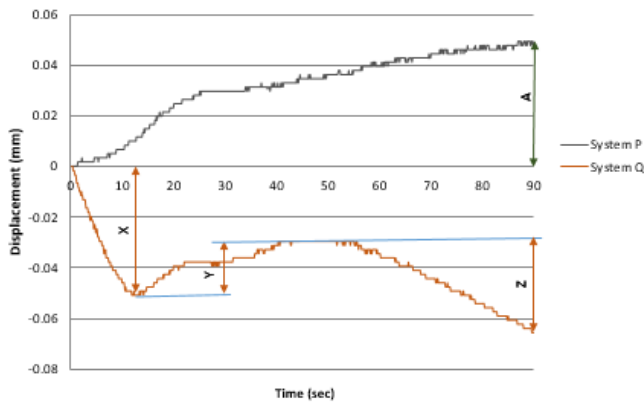


Figure 5. The previous measure of longitudinal distortion, D_L .

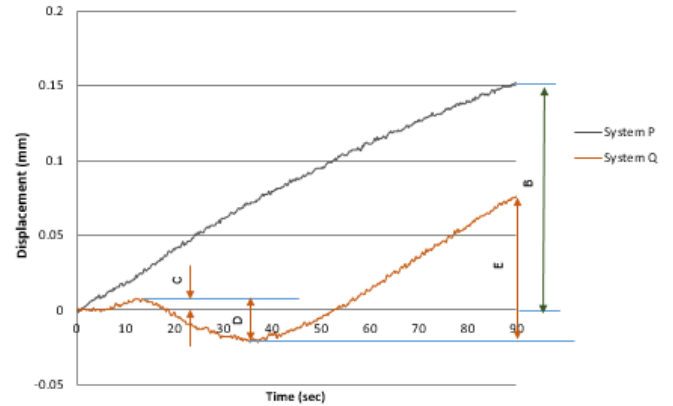


Figure 6. The previous measure of radial distortion, D_R .

The previous approach only allowed thermal distortion to be represented as absolute values from the TDC. This approach was confounding. A new approach for measuring thermal distortion is based on the area between the TDC and a reference line. Calculating distortion uses a numerical integration method of the trapezoidal rule. The distortion is calculated as displacement multiplied by time (mm*sec.) or the area between the TDC and a reference.

A system is considered thermally stable (no displacement longitudinally and radially) if the TDC is a horizontal line on the origin. Figure 7 shows that D_L is based on area between the TDC and the horizontal axis as the reference. D_L for “System P” is represented as the green shaded area above the horizontal axis and D_L for “System Q” is represented as the brown shaded area below the horizontal axis.

Figure 8 shows that D_R is based on area between the TDC and the horizontal axis as the reference. D_R for “System Q” is represented as the blue shaded area between the TDC and the horizontal axis.

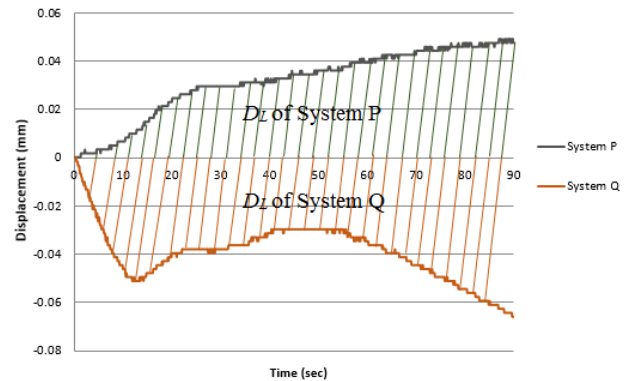


Figure 7. A new approach for longitudinal distortion, D_L .

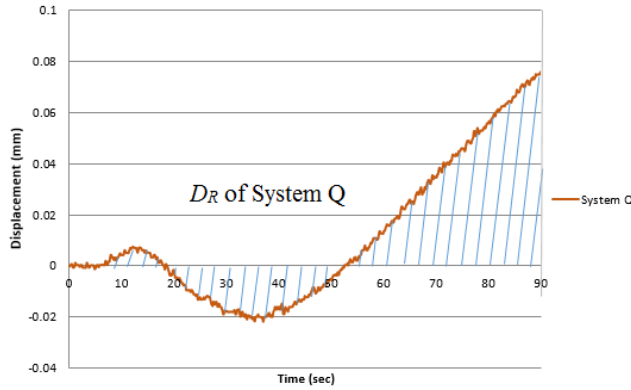


Figure 8. A new approach for radial distortion, D_R .

The D_R indicates outward expansion of the disc-shaped specimen. For longitudinal distortion (D_L), it is possible to differentiate between expansion (upward movement of the curve) and plastic deformation (downward movement of the curve) separately from the TDC. In this investigation, the authors chose to record the total distortion (T_D) stated in Eqn. 1 as:

$$T_D = D_R + D_L \quad \text{Eqn. 1}$$

Further, the distortion radial (D_R) indicating expansion was monitored using a high speed laser micrometer scanning sensor (resolution of 0.05 μm). A detailed procedure for the TDT has been defined in the “AFS Mold and Core Test Handbook.”⁴

Change in mass

Prior to TDT each specimen was weighed. Following TDT the surface of the specimen was blown with 0.07 MPa (10 psi) air pressure to remove any loose sand grains. The specimens were then again weighed, and the percent change in mass was recorded. Next, the specimens were visually examined for signs of thermally induced cracking of the surface, loss of sand where contact was made with the hot surface, and any other discolorations. Losses at this heat-affected-zone (HAZ) may be indicative of the tendency to produce cuts and washes, erosion/inclusion type defects. In interpreting this data, it is critical to identify the components causing the change in mass. The percent change in mass was calculated based upon the difference between the weight before and after as a percent of the weight before. All percent changes in mass values represent the percentage of weight lost.

3. OBSERVATIONS

Prior to elevated temperature exposure each specimen was weighed. Following elevated temperature exposure, the surface of the specimen was blown with 0.07 MPa (10 psi) air pressure to remove any loose sand grains. The specimens were re-weighed, and the percent change in mass was recorded. Next, the specimens were

automatically examined with a 3D Macroscopic for discolorations, signs of thermally induced cracking and/or loss of sand where contact was made with the hot surface.⁷

Dimensional data regarding cracks and sand binder losses will be collected using a one-shot, non-contact 3D Measuring Macroscopic (3D-Macroscopic) manufactured by Keyence (Model - VR 3100). This measurement system also allows the surface of the disc-shaped specimen to be captured (at ambient or elevated temperature).⁷

RESULTS AND DISCUSSION

Results are shown in Tables 2 and 3. All specimens were tested at 1000C (1832F) and 1400C (2552F). The TDT and percent change in mass results at 1000C (1832F) are presented according to percent PUCB binder in each sample (Table 2). Similarly, TDT and percent change in mass results at 1400C (2552F) are presented according to percent PUCB binder in each sample (Table 3). In addition, temperature versus time plots and photographs of the PUCB specimens before and after TDT at different temperatures are presented in Fig. 9 through 12 and Tables 4 and 5.

Table 2. Thermo-mechanical Properties of PUCB Samples at 1000C (1832F)

PUCB Sample	Results of Thermal Dist. Testing @ 4.50 N for 90 seconds at 1000C (1832F)			Observation During Elevated Temp. Testing	
% Binder	D_L Longitudinal (mm*sec)	D_R Radial (mm*sec)	T_D Total Dist. (mm*sec)	% Change in Mass	Cracks and Fractures
0.9	5.78	13.61	19.39	4.9	faint
1.4	5.55	8.16	13.71	1.3	large

Table 3. Thermo-mechanical Properties of PUCB Samples at 1400C (2552F)

PUCB Sample	Results of Thermal Dist. Testing @ 4.50 N for 90 seconds at 1400C(2552F)			Observation During Elevated Temp. Testing	
% Binder	D_L Longitudinal (mm*sec)	D_R Radial (mm*sec)	T_D Total Dist. (mm*sec)	% Change in Mass	Cracks and Fractures
0.9	20.22	17.37	37.59	14.0	large
1.4	10.14	19.96	30.10	5.2	large

TDT

The TDCs for all systems tested showed undulations that indicate thermo-mechanical and thermo-chemical changes in the binder system at elevated temperature.^{2,5} For specimens tested at 1000C (1832F), the longitudinal distortion curves showed plastic deformation (downward movement of a TDC) after ~ 35 seconds (Fig. 9). The radial distortion (D_R) clearly indicated an expansion trend (Fig. 9).

At the lower test temperature specimens had similar TDCs and the two binder levels (0.9% and 1.4%) were not significantly different in longitudinal distortion (Fig. 9, Table 2). These findings are supported by the temperature versus time data where thermal gradients were similar (Fig. 10).

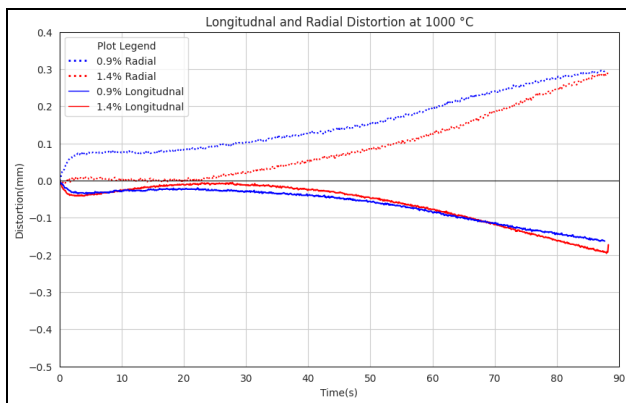


Figure 9. Longitudinal and Radial TDC for 0.9% and 1.4 % PUCB specimens at 1000C (1832F).

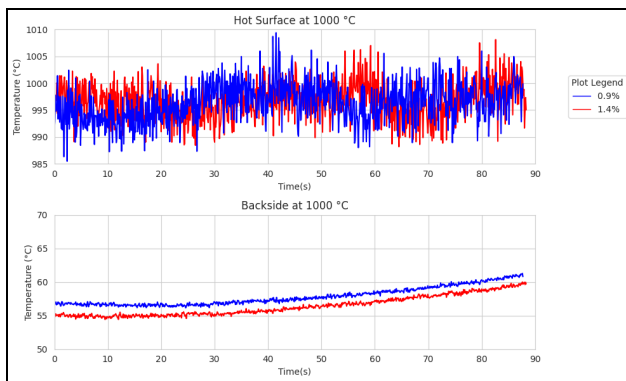


Figure 10. Temperature versus time plots between the hot surface and the back of specimens at 1000C (1832F).

For specimens tested at 1400C (2552F), the longitudinal distortion curves showed plastic deformation (downward movement of a TDC) at the start for the lower binder level and after ~ 20 seconds for the higher binder level (Fig. 11). The radial distortion (D_R) clearly indicated an expansion trend with a greater rate of expansion for the first ~ 40 seconds (Fig. 11).

At the higher test temperature, the TDCs for specimens were different and the two binder levels (0.9% and 1.4%) were significantly different (Fig. 11, Table 3). This finding is supported by the temperature versus time data where thermal gradients were dissimilar (Fig. 12). Noticeably, at the higher test temperature longitudinal and radial distortions from the TDC increased significantly especially for the lower binder level (Fig. 11, Table 3). At the higher test temperature, the hot surface showed an initial drop in temperature as the disc-shaped specimen came into contact. Still, the temperature versus time data indicated a difference in the steeper thermal gradients and the 10° difference between the two binder levels (Fig. 12).

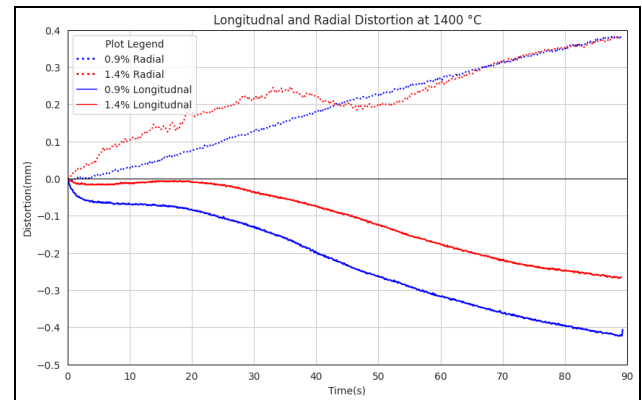


Figure 11. Longitudinal and Radial TDC for 0.9% and 1.4 % PUCB specimens at 1400 C (2552F).

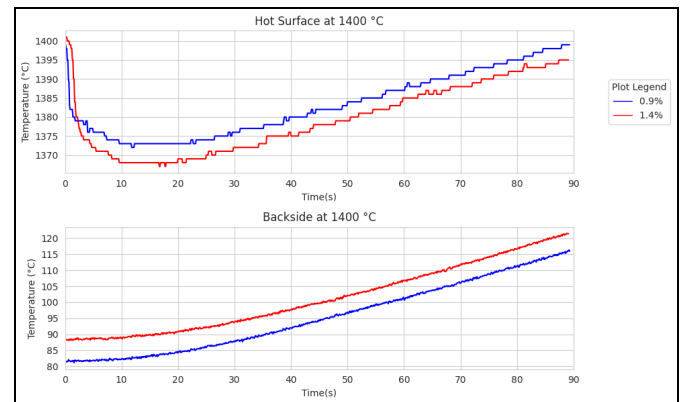


Figure 12. Temperature versus time plots between the hot surface and the back of specimens at 1400C (2552F).

MASS CHANGE

There are considerable heat induced thermo-chemical reactions occurring in both PUCB samples as is evident from the surface cracks found on all tested specimens. Furthermore, the percent change in mass values (Tables 2 & 3) ascertains the significant losses occurring at the hot surface/specimen interface. Expansion cracks were macroscopically evident on all specimens. At the hot surface/specimen interface is where binder bridges pyrolyzed and sand grains broke loose.^{2,3,5}

Tables 4 and 5 shows images from a 3D Macroscope.⁷ The first row show images of the as-received specimen's surface before TDT. The second row shows specimens after TDT; and after the loose material was blown away. The third row shows the backside of specimens after TDT. The crack propagation was more pronounced in the 1.4% PUCB specimens. The percent change in mass for all systems tested is shown in Table 2 and 3. The 0.9% PUCB specimens had more mass losses when compared to the 1.4% PUCB specimens and this was significantly greater at the higher test temperature (Tables 2 and 3).

Observations from the heat-affected zone of specimens tested are shown in Tables 4 and 5. The hot surface/specimen interface showed a crater with black discoloration due to binder degradation, the discoloration was present on the backside of the specimen. As expected this was greater for the specimens tested at the higher temperature (Tables 4 and 5). In addition, sand binder losses were evident at the hot surface/specimen interface where binder bridges pyrolyzed and sand grains broke loose. The loose sand at the hot surface/specimen interface was white. Expansion cracks were macroscopically evident on the specimens. These issues were always greater for the specimens tested at the higher temperature (Tables 4 and 5).

Table 4. PUCB Specimens Before and After TDT at 1000C (1832F)


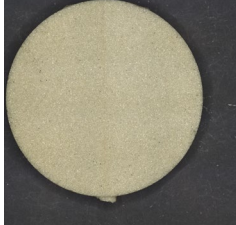
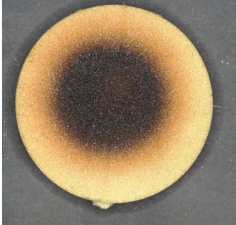
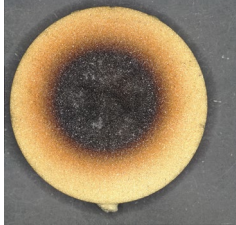
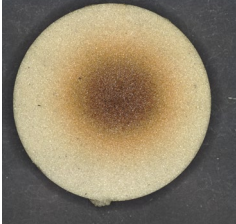
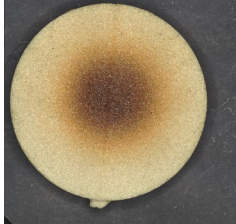

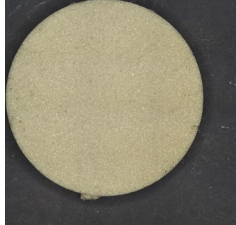
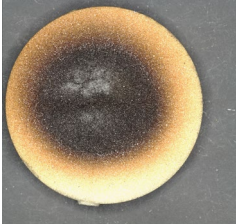

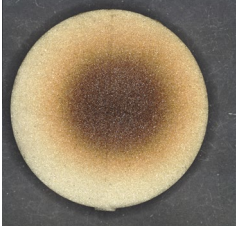
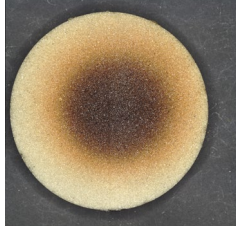
	0.9% PUCB disc	1.4% PUCB disc
Before TDT		
After TDT		
Backside		

Table 5. PUCB Specimens Before and After TDT at 1400C (2552F)

	0.9% PUCB disc	1.4% PUCB disc
Before TDT		
After TDT		
Backside		

LIMITATIONS

The effects of cast metal chemistry on PUCB systems were not considered in this study. The work in this paper represents the data for two PUCB sand samples at ferrous superheat temperatures and pressure representative of a medium-size iron casting.

CONCLUSIONS AND RECOMMENDATIONS

The thermo-mechanical changes brought forth are in the form of TDC, mass loss, and cracks on the surface of the test specimens. There was no difference in distortion (longitudinal and radial) between the 0.9% and 1.4% PUCB specimens at 1000C (1832F) with a 4.50 N (1.01 lb_f) load representing 20 cm (8 inch) cast iron metallostatic head pressure. However, when only test temperature was increased to 1400C (2552F) thermal distortion and mass loss increased geometrically.

The increased elevated temperature at constant pressure did promote distortion of the PUCB specimens. The TDT was able to capture and record both longitudinal and radial distortion curves. Further, time versus temperature data across the specimen was acquired. Heat transfer and thermal gradient information is important input data for solidification simulation programs.

Achieving TDT temperatures near superheat conditions is beneficial since it will better represent the casting trials that supplement testing. The relationship between TDT data and cast dimensions requires simulation and casting trials to be conducted in order to validate the TDT test data. Additional chemically bonded sand systems should be studied. Further work could be done at different loads and temperatures simulating various other cast alloys and pressures representative of larger or smaller castings. It is recommended that thermal imaging be used in conjunction with the TDT to investigate the radial deviation with respect to heat transfer.

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