Thermo-Mechanical Testing of Shell Resin Coated Sand using a Rectangular Bar and a Disc-Shaped Specimen

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ABSTRACT

Shell resin-coated sand (RCS) technologies have been widely used for decades by the foundry industry to produce precision sand castings. These technologies are preferred due to various advantages, such as higher strength per unit of sand, high dimensional stability and superior as-cast surface smoothness. However, binder formulation, curing parameters, additives, sand type and distribution together with alloy fill parameters can affect the intended outcome of near-net-shaped casting. This study uses thermal mechanical instruments to quantify distortion in RCS. The RCS is tested using a rectangular bar and a disc-shaped specimen and testing benefits related more to the disc-shaped specimen.

KEYWORDS: hot-box, resin coated sand, shell sand, thermal distortion curve, thermal distortion test, 3-point bending.

INTRODUCTION

SHELL RESIN COATED SAND PROCESS

RCS represent a significant portion of the numerous chemically bonded sand systems used globally to produce precision sand castings. Therefore, understanding the behavior of cured resin-coated sands (RCS or shell) when in contact with molten metal is of great interest to the foundry industry. Shell cores and molds have always been associated with high quality castings; however, concerns with emissions, odor, and low productivity opened the door in the 1970's for many of today's no-bake and cold-box binders. Since its development in Germany during World War II, the Croning, or shell process has undergone several stages of evolution. Most recent advancements in resin coated sand technology have addressed many of the concerns with emissions and productivity. Typical concerns of shell users include emissions of free phenol, free formaldehyde, and ammonia in and around their core-making facility. By changing the chemical makeup of the reactants used to form and cure shell sand, suppliers now offer a resin coated shell sand with fewer hazardous air pollutants and reduced odor.[1]

The shell process is named for its ability to make either solid or hollow cores with a thin wall or shell. Removing the leftover, uncured sand from the core cavity or mold surface allows reuse of the RCS. Making a core or mold follows four general steps:

1. Gravity flow or blow resin coated shell sand is free flowing resin-coated sand is introduced to a hot core-box or molding pattern.
2. Heat from the core-box/pattern allows the resin to crosslinks with a co-reactant, forming a solid form of sand and resin.
3. Remove the remaining free-flowing resin-coated sand from the pattern to be collected and reused.
4. Allow the cured mold or core to cool and it is ready for foundry use.

CHEMISTRY OF RESIN COATED SAND

Thermosetting resins, when exposed to elevated temperatures convert to a liquid state from the solid state. Their viscosity gradually increases and thereafter it acquires a solid state due to a cross-linking/ polymerization reaction, even at the higher temperature.[2,3,4] The cross-linking rate of a thermosetting binder system can be controlled by the amount of cross-linker being added to the formulation. The foundry industry predominantly uses thermosetting binder systems for shell molding applications. Hexamethylenetetramine, commonly known as 'hexa,' is the most widely used cross-linking agent (co-reactant) by the industry in conjunction with a novolac resin (phenol-formaldehyde). These systems are known to possess almost indefinite shelf life under controlled environmental conditions.[4,5,6] The physical and chemical aspects of the shell cure need to be closely monitored and controlled. To produce a core or mold, the reaction of the resin and co-reactant is initiated when resin coated shell sand contacts the heated tooling (temperature between 400-600°F (204-316°C)). Controlling the combination of cure temperature and time can give a desired wall thickness. The heat causes the resin coating the sand to melt and plastically flow between the sand grains. As the heat intensifies and transfers deeper into the core, the co-reactant breaks down into formaldehyde and ammonia. The evolved formaldehyde is available to react with the hydroxyl group of the phenol-formaldehyde resin, which completely cross-links the resin polymer and transitions it from a thermoplastic to a thermoset in the fully cured, rigid state. A core or mold color of golden yellow to brown indicates a hypothetically 'complete' cure.

BENEFITS OF THE RESIN COATED SAND

Individual resin-coated sand formulations are made specific to the core, mold, or casting requirement. One of the many remarkable aspects of the shell process is its ability to utilize successfully almost any type of aggregate found in the foundry. A few common variations to formulations can include aggregate type and size, resin type and amount used (typically between 1.0-6.0%), plasticizers, and additives specific to the end use of the core or mold. Further additives such as clay, oxides, inhibitors, and shakeout enhancers can be custom blended into the sand formulation during the coating process. The coating technology for shell sand has been well documented by Kerns et. al.[1]

Cured resin-coated sand has several advantages for the end user. They are completely thermoset and are not prone to plastic deformation with the extreme heat experienced during casting. Another advantage is most shell cores are hollow and molds thin and lightweight, due to the high strength to sand ratio of RCS. These attributes result in significant savings in sand usage, handling equipment, reduced waste, alongside improved employee ergonomics and safety.[1] Nevertheless, moisture in the shell sand, either by condensation or introduced via an air-line, will inhibit the sands ability to flow and achieve full density. Low density RCS can cause problems such as lower strength, peel-back, or delamination defects. There are no concerns about bench-life during downtime, as once the core or mold is made it has unlimited shelf life and is unaffected by moisture.[1]

TESTING SHELL RESIN COATED SAND

Testing methods that provides information on shell RCS core and mold quality is a requirement in foundry operations. In the United States this is commonly done by evaluating the hot and cold tensile strength of the cured shell RCS. The standard dog bone tensile, transverse tensile and disc transverse strength tests are three procedures used in foundries and laboratories to monitor the strength of shell RCS.

Foundry engineers have long known that there is high test-to-test variability in tensile strength testing with the AFS standard dog bone specimen. Control was unachievable due to inherent variability specimen-to-specimen and test-to-test. Understanding those variations is a key issue for achieving good process control in shell RCS.[7]
Western Michigan University (WMU) has

used a disc-shaped specimen as a supplementary test specimen in the foundry industry for twenty-five years. This specimen shape is of simple geometry a key factor that has allowed reduced specimen-to-specimen variability with the 50mm diameter, 8 mm thick disc-shaped specimen. A set of non-standard test methods for chemically bonded sands using disc-shaped specimens has been developed at WMU; namely: density, abrasion, impact, hot-permeability, and thermal distortion testing (TDT). These tests have proven useful in control of chemically bonded precision sand systems.[7] Complementing the laboratory testing are various casting trials that uses the same disc-shaped specimens to evidence specimen/metal interfacial defects such as veining/penetration, distortion, erosion and gas.

The Japanese Foundry Industry uses a rectangular bar type specimen as a standard test specimen with chemically bonded sand. The chemically bonded sand specimen measures 100 mm long by 10 mm wide by 10 mm thick and is typically used with a 3-point bend test to characterize mechanical properties.

3-POINT BEND TESTING

In engineering mechanics, the 3-point bend test characterizes the behavior of a slender structural element (rectangular bar specimen) subjected to an external load applied perpendicularly to a longitudinal axis of the specimen. The 3-point bend test measures the force required to bend a beam shaped specimen under 3-point loading conditions. The 3-point bend test produces tensile stress in the convex side of the specimen and compression stress on the concave side. This creates an area of shear stress along the midline. The 3-point bend test schematic and loading is shown in Fig. 1(a) and (b) respectively.

The 3-point testing has benefits. The data is used to select materials for parts that will support loads without bending or flexing. Flexural modulus is well understood and is used to indicate a material's stiffness along with the mechanics of bending moment, max

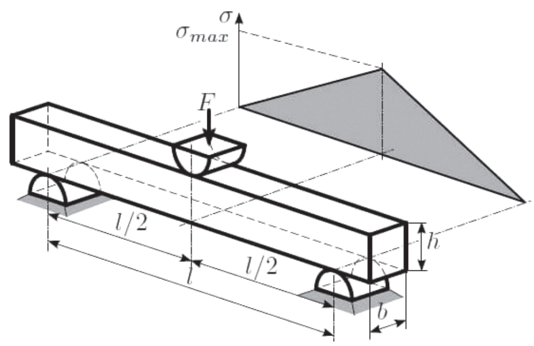

Fig. 1(a) Schematic for 3-point bend test[8]

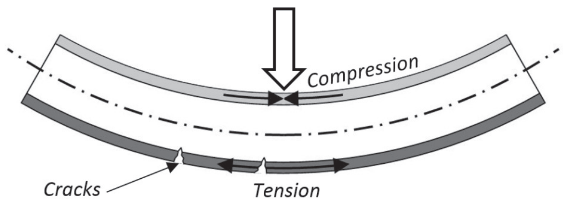

Fig. 1(b) Stress distribution[8]

stress and deflection. According to Poisson's ratio, stress is perpendicular to the bending stresses and parallel to the axis of dimension b. Therefore, at the ends of the test piece, the bending moment, and accordingly all stresses, are zero.[8] Additionally, shear stress induced, which also fluctuates based on thickness. This shear loads are responsible for strength of laminar layers and bonds. If the layers of concentration are situated nearer to the center of surface because of the proportional contraction and expansion between the layers can be inverted by testing the sample face up or face down, so there will no stress at the middle of thickness. Distortion is less anticipated there.[8]

THERMAL DISTORTION TESTING

Required of the foundry industry are test methods that accurately measure the thermal distortions of chemically bonded binder systems in real time and without the expensive and laborious process such as casting trials. The thermal distortion test (TDT) is a method for measuring the thermal distortions or displacement of cured chemical binder systems at elevated temperature and pressure in real time. The TDT uses a cured, disc-shaped specimen that offers a method to study the changes brought by the thermo-mechanical reactions of chemically bonded sand binder systems upon exposure to molten metal.

The specimen is considered a simple beam that has no orientation benefit when placed into testing apparatus (Fig. 2). The 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.[9] TDT has the capability to represent the pressures that sand binder systems will experience from molten metal filling through 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 retained strength, a visual analysis for cracks (which, in the metal casting 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, un-bonded sand generated at the mold metal interface.[9]

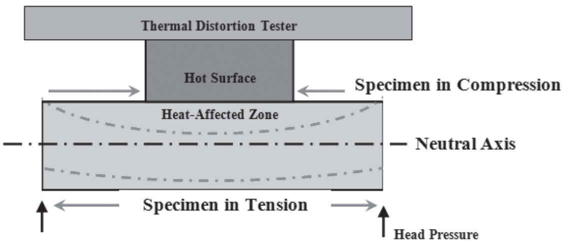

Fig. 2　TDT stresses on specimen

The functionality of the TDT is accomplished using several instruments, controllers, mechanical devices, and a computer that is used to record data. A complete description of TDT operations and testing procedure is provided in the AFS Paper No. 13-1454.[9] Further, thermo-mechanical and thermo-chemical changes in the sand binder systems at elevated temperature that causes the casting surface defects can be related to the shape, height, area and inflections on a thermal distortion curve (TDC) that is generated in real-time. An example showing how TDC's can be used to discriminate among chemically bonded sand systems is depicted in the longitudinal displacement curves (Fig. 3).

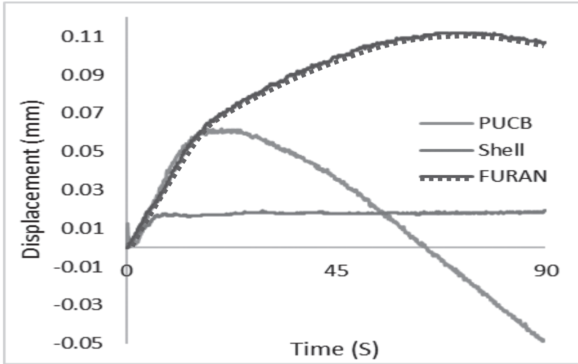

Fig. 3　Longitudinal displacement of various sand binder system

NEED AND PURPOSE

Over the decades, usage of shell RCS for foundry applications is due to various real and perceived advantages, such as higher shell/mold/core strengths, higher dimensional stability and precision, and high casting surface smoothness. These properties allow achievement of near-net shape castings.[3,4] Traditionally, cured RCS are measured and compared on physical characteristics such as melt point (or stick point), tensile strength, and/or BCIRA hot distortion curves.

By changing characteristic additives of the RCS (such as sand type, resin, or oxides), the mechanical properties can change to give the cured core or mold added benefits specific to the casting requirements. Ultimately, these variables and other factors in casting can affect the intended outcome of near-net-shaped shell RCS castings. Foundry engineers need improved testing techniques to discriminate among shell RCS samples.

METHODOLOGY

The procedures used in this section allowed the researchers to compare the thermo-mechanical properties and characteristics a shell RCS. This paper studies two specimen types; a rectangular bar and a disc-shape design when loaded at elevated temperature.

PREPARATION SPECIMENS

All specimens used in this study were prepared at Sintokogio Ltd., Toyokawa, Japan and shipped to Western Michigan University (WMU) for testing. Specimens were prepared with a shell RCS used for aluminum casting core production and sand properties are identified in Table 1.

Table 1 Properties of the shell RCS

Property	Value
Grain Fineness, AFS, Coated [screens]	55 [3]
Roundness/Sphericity (Krumbein)	7/8
pH	7.24
Melt Point, ℃	99
Rectangular Bar Specimen Mass, grams	14.75
Disc-Shaped Specimen Mass, grams	19.28
3-point Bend Strength Rectangular Bar, Pounds	23.6
Transverse Strength Disc-Shape, Pounds	40.8
Binder % or Loss on Ignition, LOI %	2.42

Note:Rectangular specimens were cured at 250℃ for 30 seconds and disc-shaped specimens were cured at 250℃ for 60 seconds.

The rectangular bar shell RCS specimen were 100 mm long by 10 mm wide by 10 mm thick and the disc-shaped shell RCS specimens were 50 mm in diameter by 7 mm thick. Fifteen of each specimen type were tested at WMU in controlled laboratory conditions: Temperature at 20 ± 1℃ and relative humidity at 50 ± 2 %.

TDT – RECTANGULAR-BAR SPECIMEN

The TDT was modified and equipped with a special hot surface point and support point to investigate a shell RCS systems. The rectangular bar shell RCS specimen is placed on two parallel support points. The loading force is applied in the middle by means of a heated hot point. In the test arrangement (Fig. 4) a rectangular bar shell RCS specimen is heated when flexed. An actuator was adjusted to represent the stress experienced by a RCS core during a casting process that was 0.01 MPa. This predetermined stress was identified to represent a medium sized aluminum casting. Next, the temperature control was adjusted to 700℃ to represent molten aluminum.

The deflection versus time/temperature curves were generated automatically using the integrated data acquisition system. The thermal deflection tests were performed over a 90 second interval, based upon solidification simulation results for a medium size aluminum casting.

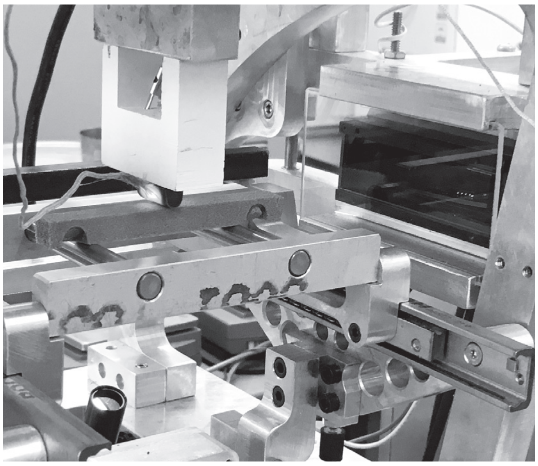

Fig. 4 TDT setup for rectangular-bar specimen

TDT - DISC-SHAPED SPECIMEN

A thermal distortion tester (TDT) was used to investigate a shell RCS systems.[9] The actuator on the TDT was adjusted to represent the stress experienced by a RCS core during a casting process that was 0.01 MPa. This predetermined stress was identified to represent a medium sized aluminum casting. Next, the temperature control was adjusted to 700℃ to represent molten aluminum.

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RESULTS AND DISCUSSION

This section relates to the findings and observations from ambient and elevated temperature testing for both rectangular bar and disc-shaped RCS specimens. Results are shown in Tables 2 and 3 and Fig. 5 through 7.

THERMO-MECHANICAL CHANGE IN SPECIMENS

Table 3 provided the physical and mechanical property information regarding the RCS specimens tested in this study. All specimens were tested at 700℃ and the test time was kept constant. The thermal distortion curves

Table 2. Thermo-Mechanical Properties of the Shell RCS Specimens

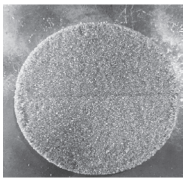
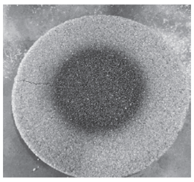
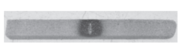
	Results of TDT @ 2.90 N for Rectangular Bar Specimen & 3.25 N for Disc-Shaped Specimen for 90 seconds			Observation During Elevated Temp. Testing	
Specimens	D_L Longitudinal (mm*sec)	D_R Radial (mm*sec)	T_D Total (mm*sec)	% Change in Mass	Cracks and Fractures
Rectangular Bar	2.14	0.03	2.17	NA	NA
Disc-shaped	3.08	10.11	13.19	NA	Visible on hot HAZ

(TDC) for the RCS systems tested showed undulations that indicate thermo-mechanical and thermo-chemical changes at elevated temperature.

Thermal distortion is the expansion, contraction, and degradation experienced by a mold or core under extreme heat and liquid pressure of the molten metal.[7,9] In a simpler sense thermal distortion is a gross term indicating a molten metal disruption as it contacts a mold/core. The disruption reveals itself as a mold/core/metal interfacial defects such as casting distortion, veins and/or penetration.

Directional heating of sand composites (mold and core media) will generate anisotropic thermal gradients in the materials. When sand composite meets molten metal, the heat transferred causes thermo-chemical reactions that result in dimensional changes in the composite. At any given temperature, these dimensional changes or thermal distortions are attributable to simultaneous changes in both the sand and the binder.[4,5] 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.[4,5] With organic chemically bonded systems such as shell RCS the reactions generally include

Table 3. RCS Specimens and Heat-affected-zones

Specimen Type	Before Testing	After Testing
Disc-Shape		
Rectangular Bar		

release of volatile materials, possible core strengthening reactions from secondary curing, and core weakening from pyrolysis. It is also important to understand and distinguish between thermo-mechanical distortions that are caused by the shell binder and the sand base aggregate.

TDT - RECTANGULAR-BAR SPECIMENS

The results for the TDT on rectangular bar RCS specimens was inadequate in that there was very little displacement occurring. Longitudinal displacement (Fig. 5) showed a relatively small amount of expansion and radially (Fig. 6) the specimens were stable at test temperature. For the rectangular bar,

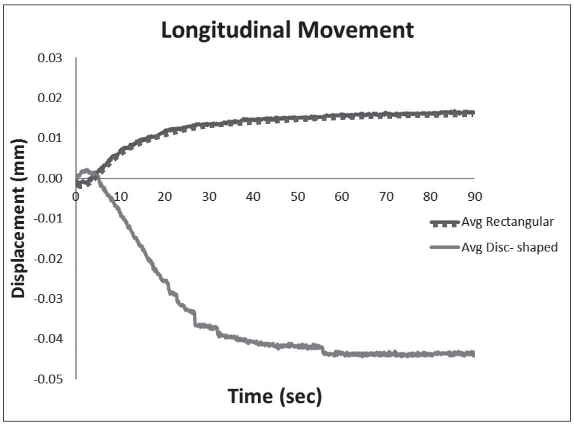


Fig. 5 Longitudinal distortion for rectangular bar and disc-shaped RCS specimens

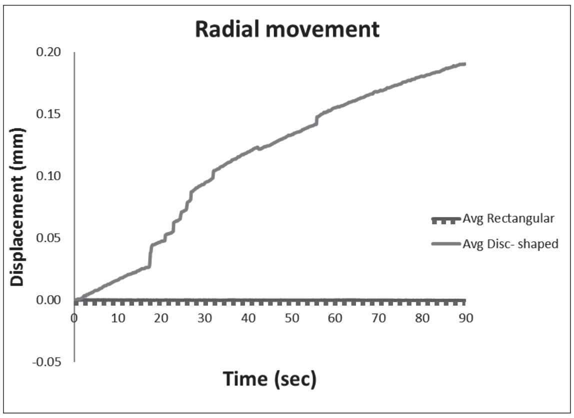


Fig. 6 Radial distortion for rectangular bar and disc-shaped RCS specimens

there were neither cracks nor fractures that appeared on the heat-affected zone (HAZ) and no change in specimen mass was detected (Tables 2 and 3).

TDT - DISCS-SHAPED SPECIMENS

The results from TDT for the disc-shaped RCS specimens was more interesting and revealing when compared to the rectangular bar specimens. During TDT of the disc-shaped RCS specimens a popping sound was heard, indicative of a specimen crack. More importantly, the inflection captured on the radial TDC indicates when that crack had occurred on the disc-shaped specimen. TDT permits an understanding of how the curing parameters (curing temperature and time) may influence the time until a crack propagates in a shell RCS core specimen. Longitudinal TDC (Fig. 5) showed an initial expansion for a few seconds followed by dramatic plastic distortion for ~30 seconds. The radial TDC showed expansion (Fig. 6) for the duration of the test. The disc-shaped RCS specimens had inflections in their TDC's that indicate the occurrence of a crack. The disc-shaped RCS specimen crack occurred at ~20 seconds with an average crack size of 0.02 mm. Interestingly, if these cracks had emerge prior to the metal solidification, a mirrored casting surface defect would ensue. Radial displacement of disc-shaped RCS specimens at elevated temperature is certainly more prevalent when compared to rectangular bar RCS specimens. Fig. 7 shows that there was certainly more heat transfer from the hot surface to the backside of the specimen in case of the disc-shaped specimen

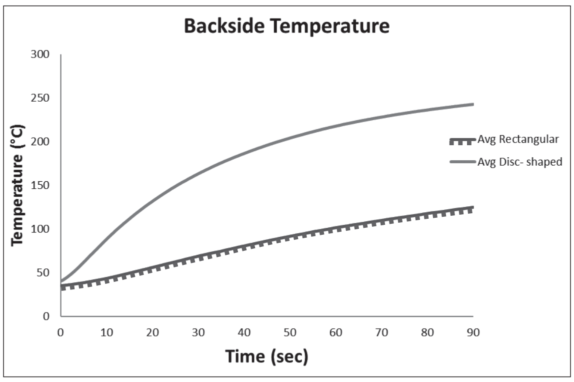


Fig. 7 Temperature versus time plots between the hot surface and the back of rectangular bar and disc-shaped RCS specimens

compared to the rectangular bar specimen.

After TDT the resulting HAZ of the RCS revealed a dark discoloration where the sand binder did remain intact though partially pyrolyzed. The cracks and fractures were clearly visibly evident after TDT. However, with the aid of a 3D Macroscope the cracks were made apparent.

LIMITATIONS

The work in this paper represents only one shell RCS system. There are many other shell RCS systems not to mention the systems containing additives from which additional thermo-mechanical property data could be gathered.

CONCLUSIONS AND RECOMMENDATIONS

The 3-point bend test was used to characterize the behavior of a rectangular bar shell RCS specimen when subjected to a hot external load applied perpendicularly to the longitudinal axis of the specimen. In this study, a rectangular bar shell RCS specimen was heated when flexed. For a brittle material like shell RCS a time to failure (bend) at temperature and maximum stress at failure it is called modulus of rupture (MOR). It was unclear how modulus stiffness can be determined from the current test arrangement. Moreover, this study points out that the TDT on rectangular-bar specimens was not sensitive to specimen heating, loading geometry and strain rate. Further, the loading procedure utilized does not fail the specimen in elastic/plastic deformation and heat transfer to the rectangular bar specimen was low. Thus, the researchers were unable to obtain output data such as the Thermal Flexural Strength (Modulus of Rupture – stress required to fracture a specimen in a hot bend test) and Thermal Flexural Modulus (Modulus of Elasticity – calculated from the results of a hot bend test, giving the slope of the stress-deflection curve).

The TDT method described in this paper can be used to detect thermo-mechanical issues in shell RCS; the disc-shaped specimens help identify the radial distortion and shell cracking issues. The longitudinal and radial TDC showed thermal distortions since there was greater heat transfer through the disc-shaped specimen. The disc-shape specimen is of simple geometry that can be easily incorporated in the hot-box at the parting-line and vented to produce specimens of various thickness during shell RCS core/mold production. The disc-shaped specimen remains a non-standard specimen that can be used to study external and internal sand additives. The disc-shape specimen offers the opportunity for more than TDT. The disc-shaped specimens are used for physical and chemical property testing.[7,9] Complementing the laboratory tests are casting trials that uses the same disc-shaped specimens to evidence specimen/metal interfacial defects such as veining, penetration and distortion.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Sintokogio, Ltd. for the research support; J. Wheeler from Exactheat for electronic heating solutions and G. Hall, P. Thannhauser and M. Konkel from WMU for technical support.

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