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Digital and Agile Moisture, VOC, and LOI Testing Using Induction Heating Technology

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ABSTRACT

The foundry industry depends upon testing measurements of moisture content (MC), volatile organic compounds (VOC), and loss-on-ignition (LOI) to manage sand systems. At the 2024 *AFS Metalcasting Congress*, a "Fast MC, VOC, and LOI Test" capable of achieving digital data was revealed. That technology used magnetron (M) and infrared (IR) technologies that are faster than conventional laboratory approaches for running all three tests independently.

This study identifies the use of a singular heating technology to achieve rapid MC, VOC, and LOI testing in a single unit. A prototype tester has been developed using induction heating technology capable of completing all three tests in series.

The induction heating technology for fast moisture content, VOC, and LOI requires a new control regime. The overall cycle time for the three tests in series is approximately 15 minutes, which is considerably shorter than previously investigated heating technologies.

Keywords: Foundry 4.0, induction, infrared heating, loss-on-ignition, LOI, magnetron, M, moisture content, MC, volatile organic compounds, VOCs

INTRODUCTION

The foundry industry depends upon the test measurements of moisture content (MC), volatile organic compounds (VOC), and loss-on-ignition (LOI) to manage sand systems.[1,2] The MC, VOC, and LOI are important property tests for green and chemically bonded foundry materials.[1-6] By monitoring MC, VOC, and LOI, the foundry engineer can check on related components of the sand system. These AFS standardized thermo-gravimetric tests have been an important quality control measure carried out in foundry sand labs and Foundry 4.0 requires an inline approach. Applications for the inline approach include new sands, green sand systems, chemically bonded cores and molds, sand additives, and reclaimed sands. Each application has an established control range.

The AFS-defined MC, VOC, and LOI tests use an oven for MC and different types of furnace designs for the other tests. These heating approaches are time consuming, often requiring hours.[7] A modified method, using a microwave furnace, provides results in about 20 minutes.[8,9] With faster testing and analyses MC, VOC, and LOI can aid near-real-time process control data.[2-5,8-10]

Managing either green or chemically bonded sand systems in high production molding lines requires fast digital data in an age of Foundry 4.0. The MC is the difference in weight before and after oven drying a foundry sand sample to an AFS-defined temperature.[7] The MC is an important component in all green sand castings. Water is generally added at 2-5% of the weight of the green sand mixture, so time to complete thermogravimetric analysis (TGA) increases with the amount water. Too much MC in foundry sand will lead to gas and penetration defects. Too little MC in foundry sand will lead to friable molds and erosion defects.

In order to determine the VOC and/or LOI measurements a dried foundry sand sample is required.[7] The gases that have evolved from foundry molding sands may contain VOCs and hazardous air pollutants (HAPs) and have been shown to be major contributors to overall foundry air emissions. The VOC is the difference in weight before and after firing 480C (900F) of the dried foundry sand sample.[7]

The LOI is the difference in weight before and after firing 982C (1800F) of the dried foundry sand sample.[7] The main method for determining LOI involves heating samples to temperatures at which organic materials decompose, and certain inorganic components volatilize. The resulting loss in weight from the sample is the LOI measurement. This measurement indicates the amount of combustibles in raw sand. For green molding sand, these combustibles consume water added to activate the clay. In chemically bonded sand, they absorb binder and reduce its effectiveness. Thus, LOI measurements can provide essential information about the overall quality of a foundry's sand system.[2-6]

The VOC and LOI testing procedures defined by AFS call for the use of either a muffle or microwave furnace.[7] Unfortunately those tests are considerably slow.[2-6] The time lag between testing and results can lead to certain sand-related defects if high levels of organic materials are present in foundry sand systems. Currently, foundries cannot identify the organic materials in real time. The presence of excessive organic materials in foundry sands is problematic because some of these materials can volatilize at temperatures much lower than that required for the casting process. The outcome is usually gas porosity defects in the castings. This paper addresses those problems.

Established testing methods include the use of a muffle furnace, a magnetron (M), an induction coil, and infrared (IR) to heat the sand sample.[2-9] The muffle furnace method is quite time consuming in order to fully remove all of the organic materials from the sand. It takes two hours of heating the sample. While the microwave furnace method reduces the time taken in the muffle furnace method considerably, it still requires twenty minutes to conduct the test of a sample.[2-9] It is further limited to a single test of LOI without the possibility of additional testing during this destructive test. A prototype testing method using an induction coil was developed.[6] This test utilizes an induction coil to quickly bring the sand sample to its critical temperature.

This method records more information than simply LOI; it also measures the moisture content and volatile organic compounds of the sand sample in less than ten minutes. However, induction heating technology posed challenges with the control of instrumentation. Ultimately, the researchers successfully switched the heating technology to infrared (IR).[2-5]

Without the ability to monitor real time properties of sand, casting defects such as gas can occur.[1-6] The LOI is an important measure of non-active combustibles within the sand system.[1-5] In 2022, an automated inline technology for LOI testing was developed to move towards Foundry 4.0.[2-4] Until now no AFS testing technology has been shown that would achieve fast MC, VOC, and LOI measures within a single test unit.

PURPOSE

The MC, VOC, and LOI are recognized tests for evaluating foundry granular materials.[7] It is time consuming, requiring up to three hours for the LOI test using a muffle furnace. A modified method, using a microwave furnace, provides results in approximately twenty minutes.[2] However, the cooling cycle is long which delays the start of the subsequent measure. This represents a significant reduction in the time required to run the test. Unfortunately, with cycle times for mold and cores as little as twenty seconds in the foundry industry, twenty minutes can represent a large number of affected castings during high production molding. In addition, the samples recommended are 50g for a muffle furnace or 8g for utilization in a microwave furnace.

The conventional LOI testing technology cannot be used as an inline process control tools because these samples require processing in a sand laboratory.[7] The LOI testing can be an effective quality check of chemical binder additions to sand mixes and has often been discussed as a control tool for the sand reclamation process.[7] Unfortunately, previous testing methods were too time consuming to be used in such a manner. An automated inline test of MC, VOC, and LOI to provide rapid, accurate, and reliable testing on a working foundry sand system is required. This approach can provide data for a process monitoring control tool that is commensurate with Foundry 4.0.

OVERVIEW OF THE PROBLEM

This study explores a new induction semi-automated method for reliably collecting MC, VOC, and LOI from a sample of foundry sand. The required technology needed was an induction heater capable of achieving LOI temperatures of 1832F (1000C). The induction semi-automated test utilizes induction technology together with instrumentation, actuators, data acquisition from temperature and mass sensors which are integrated with a computer to determine the percent MC, VOC, and LOI. Furthermore, specialized controls were implemented to overcome the eddy current effects caused by induction heating.

OBJECTIVES

1. Develop an automated tester as a single unit to rapidly measure MC, VOC, and LOI. The tests are performed in series using induction heating technology.
2. Develop specialized control to mitigate the issues relating to temperature and mass measurement that result from the induction heating.
3. Confirm there is no significant difference between the AFS Standard MC, VOC, and LOI tests and an automated induction test.

METHODOLOGY

The standard procedures for MC, VOC, and LOI laboratory testing are provided in the "AFS Mold & Core Test Handbook."[7] The automated equipment used in this study required the design and development of an induction power supply. Furthermore, a virtual instrument (VI) dashboard for graphs showing change in mass as a function of time and temperature are provided for sand systems studied. Real-time plots of those graphs are generated on a computer screen for monitoring the test data; in addition, the measured data is saved for further analyses and comparison.

For automatic testing, the heating zone is within an induction coil. The foundry sand sample is placed in a MAR-247 super alloy crucible. The entire heating zone is enclosed within a refractory housing. All specimens were tested in laboratory conditions at Western Michigan

University. Ambient conditions were controlled: temperature at 70F ± 3°F (20C ± 1°C) and relative humidity at 50 ± 2%.

The instrumentation required for the automated test is a K-type thermocouple lead shield to prevent magnetic interference, which is used to monitor and provide feedback for temperature control of the heating zone during use. The measuring zone consists of a mass sensor that is capable of measurements accurate to ± 0.0001 of a gram. There are ceramic materials at the top of the sensor to protect it from the heating zone. Figure 1 shows the heating zone.

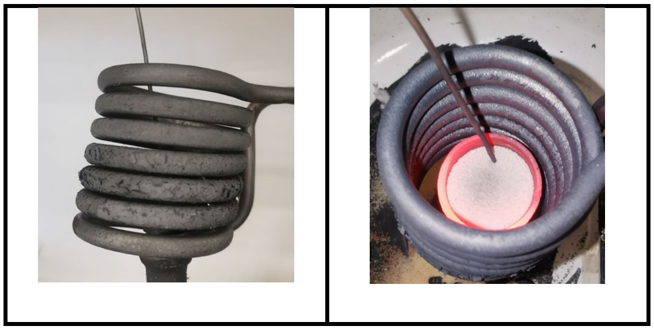

Figure 1. Crucible shown within the coils, (left - side view, right – top view).

NEW SPECIALIZED INDUCTION CONTROLS

Specialized induction controls were implemented for accurate temperature control as well as mass measurement. For the temperature control (±2°C/3.6°F) a sheathed (super alloy) K-type thermocouple was implemented for use within the induction field. The thermocouple was read through an MCP9600 amplifier board using the I2C communication protocol with a 200 millisecond response time.

A shielded loadcell was used to ensure accurate mass measurements were collected (±0.0001). Stainless steel sheeting, a ferromagnetic alloy with high magnetic permeability, and a specialized radio frequency (RF) graphitic coating was applied to prevent magnetic interference on the load cell electronics.

TESTING PROCEDURES

Two chemically bonded sand specimens and a working foundry green sand specimen were employed for this study. A sample was drawn to be used with the AFS Standardized MC, VOC, and LOI tests and simultaneously an automated test was conducted.

The AFS Standardized MC, VOC, and LOI test procedures are documented in the AFS "Mold & Core Test Handbook."[7] The newly developed automated test procedure is as follows:

1. Turn on the system to automatically center the MAR-247 crucible on the sensor within the induction coil heater prior to taring.
2. Load a 4 g (± 0.01 g) sand sample into the crucible,
3. Start the program through the user interface.
4. The program runs MC, VOC and LOI sequentially.
    a. The program monitors the rate of change of mass for each stage and when there is no change in mass at the test temperature it proceeds to the following test till completion.
    b. The program calculates the VOC and LOI for the sand sample using the weight of the dry sample at the end of the MC test.
    c. The data is recorded and displayed to the user in real time.

RESULTS & DISCUSSION

Test results from AFS Standardized MC, VOC, and LOI are compared to the new Induction Semi-Automated test and presented in Tables 1 through 3.

Table 1. Comparing AFS Standardized Results to the New Induction Semi-Automated Test – Chemically Bonded Sand - Sample 1

Test	Sample Mass (g)	Avg. MC (%)	Avg. VOC (%)	Avg. LOI (%)
Standardized AFS Test	50.00	0.05 (0.02)	2.70 (0.01)	2.75 (0.03)
Semi-Automatic Induction Test	4.00	0.06 (0.03)	2.73 (0.03)	2.76 (0.03)

Note: Standard Deviations of the 15 tests are shown in parentheses

Table 2. Comparing AFS Standardized Results to the New Induction Semi-Automated Test – Chemically Bonded Sand - Sample 2

Test	Sample Mass (g)	Avg. MC (%)	Avg. VOC (%)	Avg. LOI (%)
Standardized AFS Test	50.00	0.04 (0.03)	5.45 (0.03)	5.93 (0.03)
Semi-Automatic Induction Test	4.00	0.04 (0.03)	5.47 (0.03)	5.94 (0.03)

Note: Standard Deviations of the 15 tests are shown in parentheses

Table 3. Comparing AFS Standardized Results to the New induction Semi-Automated Test – Working Green Sand

Test	Sample Mass (g)	Avg. MC (%)	Avg. VOC (%)	Avg. LOI (%)
Standardized AFS Test	50.00	2.61 (0.03)	1.62 (0.03)	1.83 (0.03)
Semi-Automatic Induction Test	4.00	2.62 (0.03)	1.61 (0.03)	1.82 (0.03)

Note: Standard Deviations of the 15 tests are shown in parentheses

Figures 2-5 show the VI plots from the user interface. It is important to point out that a test cycle comprises of three testing ranges that are represented graphically. Typical percentage change in mass for foundry sand systems tested are shown in Figs. 2 through 5. The legend for each color indicates the test range as follows; black (MC), blue (VOC), and red (LOI) for chemically bonded sand samples 1 and 2, and the green sand sample.

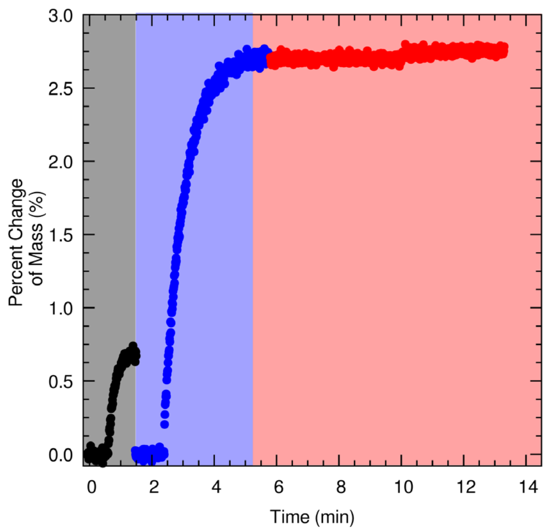

Figure 2. VI Screen Capture Showing the Typical %Δ Mass – Chemically Bonded Sand – Sample 1.

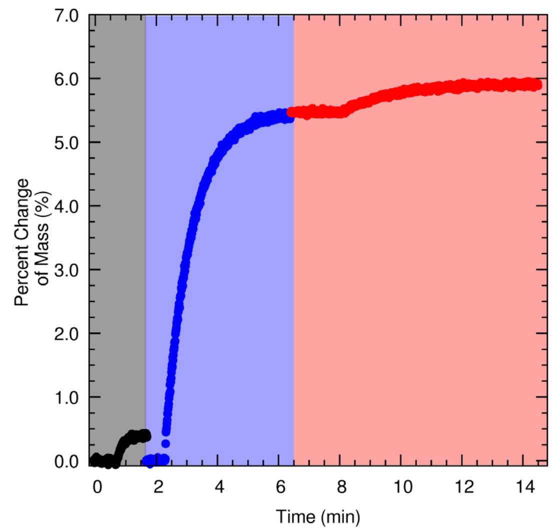

Figure 3. VI Screen Capture Showing the Typical %Δ Mass – Chemically Bonded Sand -Sample 2

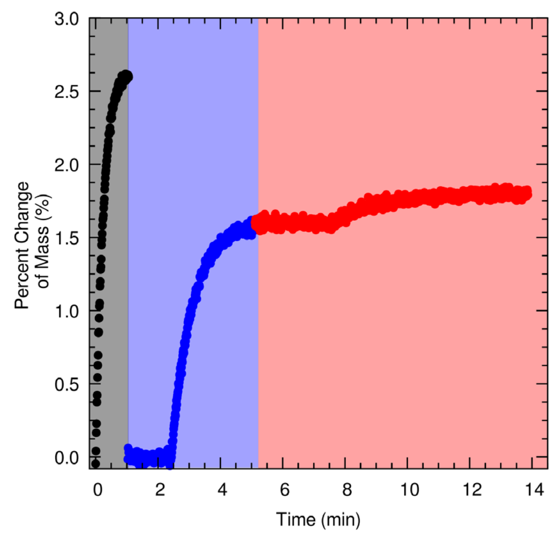

Figure 4. VI Screen Capture Showing the Typical %Δ Mass – Working Green Sand

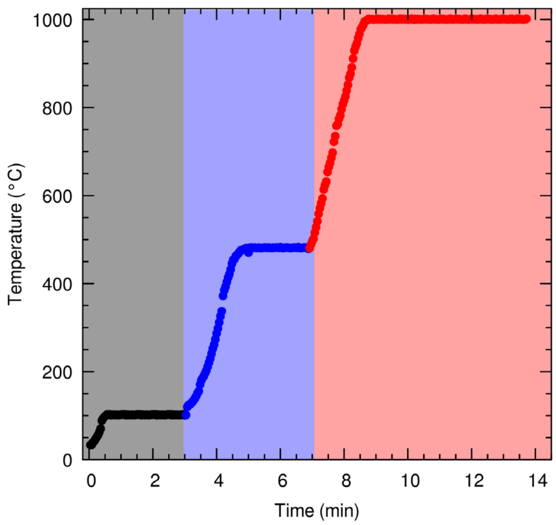

Figure 5. VI Screen Capture Showing the Typical temperature response of the heating system.

The program that was used to determine the change between MC, VOC and LOI, uses a mathematical algorithm to determine the start and end of each phase of the test, by performing a linear regression to determine the R^2 value. A testing range is deemed complete when the slope and the R^2 value approaches zero and at that point the last ten mass readings are averaged to calculate the final mass. Figure 6 represents the temperature response curve at each stage during testing. The variability of temperature is within ±3.6°F (±2 °C) at the steady state temperature at each stage.

LIMITATIONS

The work within this paper represents two chemically bonded silica sand systems and a working green sand. There are many more foundry sand systems including specialty sand, alternative molding media, and reclaimed sands that were not considered in this study.

The authors understand that there is limited data at the current stage of the research to validate the methodology identified in this paper. Moreover, the Ramrattan & Kishi AFS Paper #22-069 reveals that fast LOI measurement is achievable.[4] Ultimately, the importance of this project was to show that there is promise for fast sequential measurement of MC, VOC and LOI.

CONCLUSIONS AND RECOMMENDATIONS

The new induction semi-automatic method for rapid MC, VOC, and LOI can process a sand sample in 15 minutes including ramp time needed to reach each test temperature. The standard AFS tests were not significantly different from the new induction semi-automatic method. Moreover, the new method can be used to monitor foundry sand systems in a more agile manner.

It is recommended that the new induction semi-automatic test be employed with working foundry green, chemically bonded, and reclamation sand systems since the speed of testing and digital data output offers opportunities for faster foundry sand system process control and Foundry 4.0 analytics.

The authors plan to continue this research and will consider the issue of coil overheating. While no overheating of the coil was observed in the current research, internal water cooling might be required for continuous operation. Automated actuation for loading of the sample must be considered as well as improved induction heating technology to further reduce test cycle time. The design of the crucible shape needs to be optimized to increase the surface area contact of the sample to achieve the best heat transfer.

The aim would be to achieve a more agile test cycle. Furthermore, a fully automated inline test of MC, VOC, and LOI to provide rapid, accurate, and reliable testing to that can be fully integrated with other inline sand testing technologies for total sand control is required in Foundry 4.0.

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