AC 2007-2728: DEVELOPMENT OF APPARATUS AND PROTOCOL FOR TESTING OF SAND AT HIGH TEMPERATURES IN THE FOUNDRY

Jorge Rodriguez, Western Michigan University

Sam Ramrattan, Western Michigan University

Alamgir Choudhury, Western Michigan University

Pavel Ikonomov, Western Michigan University

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Abstract

In order to increase productivity and improve quality, the metal casting industry has realized the need for near-net shape casting. For example, in the automotive industry, power train components are designed for usage in close tolerance. One goal of the foundry engineer is to produce cores and molds of consistent dimensional accuracy, and hence a casting satisfying the tight tolerances of the automotive industry. This objective inevitably will result in improved quality and more efficient production. The developers and users of chemical binders, in hot or cold box cores or on patterns for mold, all have these issues in mind.

One of the main aspects when talking about dimensional accuracy is thermal distortion of the molds and cores. To the best of our knowledge currently there is no testing protocol to determine thermal distortion in a controlled fashion at pouring temperatures. Practitioners use data based on tests at room temperature in order to predict mold behavior at high temperatures. An apparatus and a specific methodology to measure thermal distortion have been proposed and developed by the authors, and it is reported in this paper. The proposed apparatus, now in its second generation, is simple to operate and the test specimen is a disc piece, which is already used for transverse strength testing of chemically bonded sands. The proposed protocol allows examination of thermo-mechanical properties of the specific sand-binder combination. Thermal distortion curves obtained for various sand-binder-catalyst combinations, when tested for aluminum castings, are presented.

This project was carried out over several semesters, where students in the capstone design project course sequence participated. This is a very good example of collaboration between industry and university, with benefits for both sides. The students were excited about working on a project with great potential for industrial applicability, and industry was more than willing to provide needed materials for the project to become a reality. The results obtained so far are encouraging and it is believed that the proposed methodology can be used for better process control to establish a materials control program and for dimensional control of cores and molds. The designed apparatus is another tool that would aid in identifying correct amounts of binder materials and catalysts, and for predicting the behavior of the core and mold material in thermo-mechanical application.

Introduction

Even with the promises of several alternatives for sand as a medium for the production of molds and cores for the metal casting industry, close to 90% of annual cast metal production is still done with sand. Its versatility and ease of use foster rapid innovation in an industry where the ability to change quickly can mean survival. Sand has many pluses, but it is far from perfect. This is especially true of chemically bonded sand. The use of chemical binders in hot- or cold-core box or on patterns for molds, have one common goal: near-net shape castings. The goal is to produce cores and molds of consistent dimensional accuracy, and hence a casting satisfying the increasingly tighter tolerances of the customer.

Most of the problems with sand castings are due to variations. These variations are in the characteristics of the medium (sand) and the binding materials being utilized, as well as in the process itself. But even with those issues, the popularity of sand-binder systems keeps increasing given the other benefits provided, but the search for near-net shaped castings keeps going on in industry and in academia. In order to accomplish near-net shapes it is necessary to control the thermal distortion suffered by molds and cores, an issue that has not been studied that much in the field. The only proposed test was in 1966, the British Cast Iron Research Association[4] (BCIRA) developed a Hot Distortion Tester for Quality Control in Production of Chemically Bonded Sands. The heat source for this tester is a gas burner with no direct control over heat input. Looking at this device, it can be concluded that open flame interacting with the chemically bonded sand is not the best emulation of conditions occurring in actual foundry practice. In addition, the test piece is loaded as a cantilever beam. Small deviations or imperfections at the cantilever support result in significant distortion at the opposite end, where measurements are being taken[2]. In the metal casting process, very rarely do cores and molds experience cantilever loading.

Need and Purpose

With changing requirements for castings specified by foundries, tolerances have been constantly shrinking. More emphasis is now placed on reducing core and mold distortion during pouring of castings. Casting wall width and core thickness is continually being reduced for weight reduction, thus increasing the need for consistent dimensional integrity of castings. To adhere to these standards, it is important to be able to predict the general characteristics of each core and mold-making process[3].

The design and development of a device for investigating thermal distortion in chemically bonded sands has been undertaken. The device should be capable of placing variable loads on sand-binder samples at metal pouring temperatures. The device, developed at Western Michigan University, has the objective to provide a more realistic and appropriate indication of the expected performance of sand-binder combinations in the foundry. The development of the apparatus, and the respective testing protocol, started as a Senior Project where the initial concept was checked out. After the concept was demonstrated, subsequent Senior Projects have taken place, where practitioners in industry and professional society have participated with their knowledge. Senior projects are capstone design projects that all students in the College of Engineering and Applied Sciences need to take. Teams of 3 (preferred) students work over two semesters on a project under the supervision of a faculty advisor. Valuable input and insight has been gained thru this process. At the same time, vendors and suppliers of materials have as well contributed to the project, activity that has helped in developing a more robust device and protocol. Senior projects are capstone design projects that all students in the College of Engineering and Applied Sciences need to take. Teams of 3 (preferred) students work over two semesters on a project under the supervision of a faculty advisor. The participants in the projects for this development were Manufacturing Engineering Technology and Graphics and Design Technology students.

The device has undergone several design modifications that has improved its performance, ease of use and safety. The basic functionality of the apparatus, with its design features, is discussed and sample distortion curves from testing are presented. The results obtained so far indicate that this apparatus is a very useful tool to generate comparative curves that can be utilized during initial selection of sand-binder materials.

Apparatus for Distortion Testing

The initial design was based on the basic requirements for the apparatus: a device that is capable of applying specific temperatures under a contact load to sand-binder specimens. The reason for these basic requirements is that a compressive load is a closer emulation of pour-filling operations, and having the capability to specify any temperature it will emulate use of different molten metals. The contact load can be considered as a better representation of pouring loads after initial flow impact. The test specimen is similar to the one already been used in industry (for transverse shear strength), it is a disc specimen (5.0 cm diameter by 0.80 cm thick) and it eliminates any possible effect due to the shape of the specimen. The specimen is simple-supported all around its circumference.

As a heat source for the first generation apparatus it was decided to have a heater based on electric resistance, with the temperature being monitored via a thermocouple next to the surface of contact (Figure 1). As a measuring device for distortion, an LVDT was selected, and a data acquisition system was used to monitor temperature and displacement. This initial device was implemented with mostly existing, old equipment in the College labs, which was adequate for our purpose of demonstrating the concept of a thermal distortion test. The only component that we needed to spend money on was the heating element. After several modifications (same Senior Project group) the initial device gave acceptable results, with the heating element being the main source of problems. Looking at the options, it was decided to move away from the electric resistance heat source, even when there really was no budget for the project. It is when collaboration with industry was pursued.

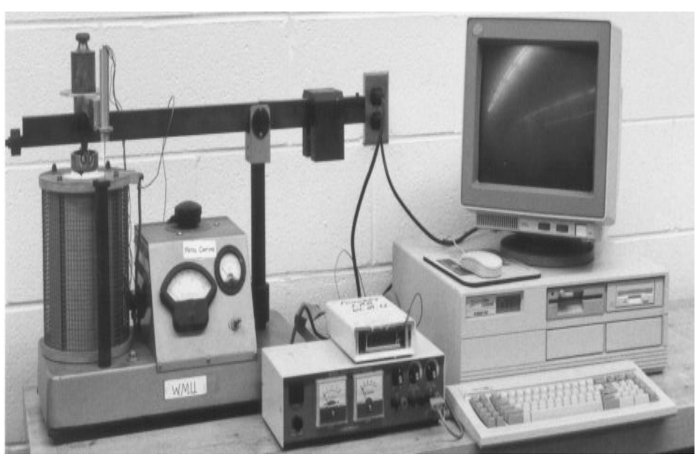

Figure 1 - Thermal Distortion Tester – First Design

The second-generation machine (Figure 2) was designed under a different senior project, which took place one year after the first machine was already functional. During that time, testing of specimens with the first machine was carried out, thus allowing us to define a robust protocol for testing. The main design change in the second machine is the utilization of an induction furnace as a source of heat. Additionally, there were changes made to improve the operation and safety of the apparatus, mainly (Figure 3):

- A lever system was implemented for more accurate measurement of distortion
- A cam was utilized to have a smooth application of the contact load
- Guards were designed for safer operation
- Improved data acquisition system

Figure 2 - Thermal Distortion Tester – Second Design

The new apparatus has several advantages over the previous one, with all of them being needed features in today's metal casting industry because foundries can no longer tolerate the extreme variability in testing caused by an inconsistent testing or lack of adequate data. The new device offers better repeatability due to a far more consistent heat source, the thermal distortion tests can be run to simulate various temperature setting, for example 760°C for aluminum, 1210°C for brass, and 1375°C for cast iron. In addition, the test piece is subjected to a more uniform direct contact with the heat source thus simulating the pressure exerted by molten metal. The compressive load applied to the specimen as it experiences the specified temperature is similar to the type of mechanical and thermal stresses that causes core and mold failures in actual foundry practice. As a clean heat source is used in conjunction with the test piece, a qualitative evaluation of smoke creation is possible as well with the new thermal distortion tester (TDT). Additionally, based on the initial mass of the specimen and its mass after thermal distortion testing, an indication of specimen degradation can be determined, thus helping the practitioner in deciding the level of mold/core disintegration expected during the casting process.

This second-generation machine had more issues for students than the first one. For the first design, being the novelty of the concept, the students were not able to have to much input in the design or implementation process, but they did experience the interaction with experts in the field while doing evaluation and searching for implementation options. For the second machine, the students had an existing device and it was a more dynamic and interactive process between faculty and students because it was a modification/improvement task. There was not that much interaction with the previous team because of the period of time between designs. More interaction existed between the senior project teams that sequentially participated in the complete development and use of the second machine. The transfer of information in this case was without problems because every semester there is a new set of 2-semester senior projects. The interaction between students and industry in this second machine went from gathering information from experts/practitioners to requesting and evaluating test specimens from users and vendors.

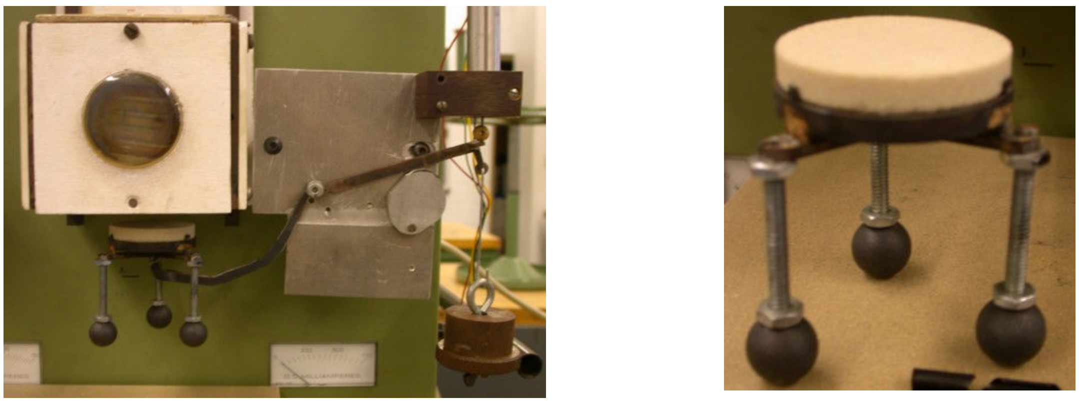

Figure 3 - Specific Features for Second Design.

Testing Protocol

The methodology proposed for testing was established after several runs have been made. Test length was the main parameter that needed to be defined. During the test there needs to be enough time to get to steady state in terms of temperature, for consistent load-temperature to be applied to the specimen, and for reliable data collection to take place. Additionally, the proposed procedure collects data (e.g., shear strength, mass degradation) that is useful in the task of predicting behavior of sand-binder combinations.

The protocol consists of four major steps[5], with all specimens being prepared and tested in a controlled laboratory environment (Temperature is controlled at 23.9±1.1C (75±2F), and relative humidity is controlled at 50±3%). The steps are:

1. Preparation of disc specimen
2. Disc transverse strength testing
3. Scratch hardness testing of specimen
4. Thermal distortion testing at specified loads for 3 minutes

1. Preparation of Disc Specimens
Materials: Silica sand (Illinois AFS/gfn 50, rounded and neutral pH) and binders. *Equipment:* Laboratory sand mixer, jig and fixture for 5-cm diameter x 0.80-cm thick disc-shaped specimen. *Procedure:* The binder to sand ratio is the one specified for testing, typically based on a percentage of weight. The sand and binder were mixed for two minutes. The test pieces were prepared by blowing the mixture at 552 KPa air pressure from a core-shooter into the disc-shaped specimen jig and fixture. The disc-shaped specimen jig and fixture has removable plates so that, after curing, the test piece can be easily removed without deformation, and can be placed on a flat surface to complete the hardening process. The strip time was six minutes.

2. Disc Transverse Strength Testing
Materials: Disc specimen. ***Equipment:*** Tinius Olsen testing machine equipped with disc-shaped specimen holder and blade for performing the test. ***Procedure:*** The disc specimen is fitted into specimen holder on the testing machine and it is supported on its ends. It is then subjected to a transverse force by applying the load with a 3-mm thick blade across its diameter. Loading is performed at a constant load rate 0.25 cm/min. A load-cell electronically senses and responds to specimen failure. The maximum load at failure is measured and digitally displayed.

3. Scratch Hardness Testing
Materials: Disc specimen. ***Equipment:*** Scratch hardness tester. ***Procedure:*** Testing of specimens is performed according to standard AFS Scratch Hardness Test 318-87-S[1].

4. Thermal Distortion Testing
Materials: Disc specimen. ***Equipment:*** Thermal distortion Tester (TDT). ***Procedure:*** To operate the apparatus, electrical power is switched on and the amperage adjusted to simulate a specific molten metal temperature for example a simulated 760°C for aluminum. The computer and data acquisition system is switched on for monitoring and plotting graphs for temperature versus time and distortion versus time (duration of test: 3 minutes). The specimen is inserted into the holder designed for the test piece. The specimen is lowered until a direct symmetrical contact is made with the 2-cm diameter heat source. This action simultaneously engages the linear displacement transducer that measures distortion (i.e., displacement between support points and center of the specimen). The test is performed with a predetermined load of 5 N to simulate hydrostatic force pressing against the core or mold. The load is actually applied to the support around the circumference of the specimen. The predetermined load can be adjusted to simulate a specific force by molten metal. The data acquisition system automatically records and plots distortion versus time/temperature.

Results

Several batches (15 specimens for each batch) of tests have been tested using commercial material (sand and binders), with the specific ratios being used in industry or recommended by the suppliers. The results shown in here correspond to coated specimens. Coatings are used to improve on the characteristics of the sand-binder system, be that more thermal insulation or perhaps additional thermal conductivity. Figure 4 shows the results obtained for three sand-binder combinations, at different condition (filling temperature, one for aluminum and one for iron). From these plots it can be said that there is evidence of the effect of various parameters on the performance of a sand-binder mix, thus confirming the importance of thermal distortion data.

The curves presented here have very similar general shape, with different level of distortion, depending on the type of binder. It can be said that it was expected that higher temperatures will result in larger distortion, as seen in the figure. The curves as well show undulations that indicate thermo-mechanical and thermo-chemical changes in the binder system at elevated temperatures. All curves have an initial expansion (upward movement) before plastic deformation (downward movement). Because of the status of this test, at this point the results obtained are being used for comparison purposes only.

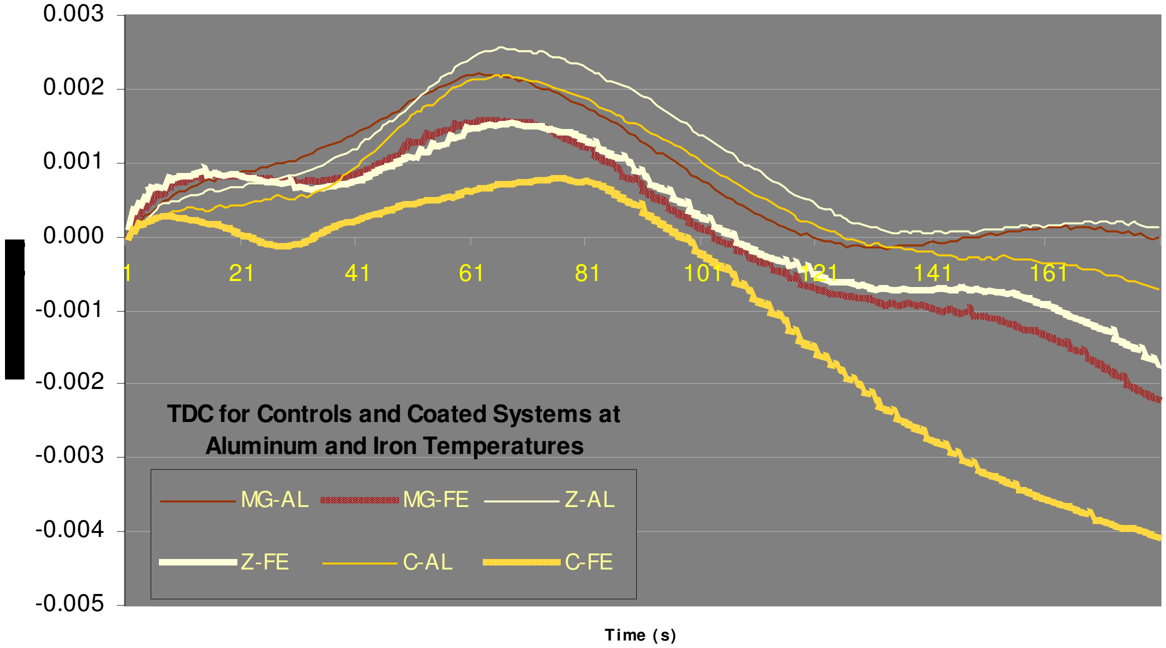

Figure 4: Thermal Distortion Curves

Closing Remarks

The proposed apparatus and protocol provide the foundry engineer with a process control tool that generates data that more closely represents the thermo-mechanical behavior of a sand/binder system during the metal casting process. Recalling that we are pursuing near-net shapes, the data provided by the developed apparatus will allow the practitioner to qualitatively – at this point – compare expected performance of the cores/molds.

There have been great experiences provided by this project to several capstone design groups. The students have benefited from the requirements to apply to the project teamwork, design and building, industry interaction (technical meetings and presentations) and project management skills; hence making their capstone experiences a well-rounded one. Linking consecutive senior projects has helped tremendously in having a smooth transition from project to project. Currently the department tries to have as many industry-sponsored projects as possible as capstone courses.

This device is by no means in its final design (Generation 3 is already on its way), but we firmly believe that there will be very more accurate and useful information produced by the new apparatus, so that the practitioner will have the opportunity to quantify the amount of distortion expected in the final shape. As this prototype equipment is improved, new information will be available (e.g., measuring loss of sand and binder due to thermal degradation, time it takes for smoke formation) to the practitioner for better designs.

Bibliography

1. AFS Mould and Core Test Handbook, 2nd ed. pp 313-314, The American Foundrymen's Society, Inc., Des Plains, IL 1989.
2. Fountaine G.C., Horton K.B.; "Comparison of Core Distortion Using Various Binder Systems," AFS Transactions, 1993, vol. 101, pp 721.
3. Kubo, K., Pehlke, R.D., "Thermal Properties of Molding Sands," *AFS Transactions*, vol. 66, pp 405-414 (1985).
4. Morgan A.D., Fasham E.W.; "The BCIRA Hot Distortion Tester for Quality Control in Production of Chemically Bonded Sands," AFS Transactions, 1975, vol. 91, pp 73-80.
5. Ramrattan, S., Butt, S., Keil, M., Rodriguez, J., "Effect of a Solvent-Based Coating on Distortion and Degradation of a Sand/Binder System," *AFS Transactions*, vol. 097, (2000).