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Methodology to Qualify and Monitor a Chemically Bonded Sand System used in Foundries

Prayag Pravinbhai Patel
Western Michigan University, prayag22@gmail.com

METHODOLOGY TO QUALIFY AND MONITOR A CHEMICALLY BONDED SAND SYSTEM USED IN FOUNDRIES

by

Prayag Pravinbhai Patel

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Doctoral Committee:

Lee Wells, Ph.D., Chair
Azim Houshyar, Ph.D.
Steven Butt, Ph.D.
Sam Ramrattan, Ph.D.

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The goal of this dissertation is to establish a new quality control framework that combines a statistical process control (SPC) approach to casting quality for chemically bonded sand systems used in foundries. Foundries in the United States use the American Foundry Society standardized sand testing to monitor chemically bonded sand systems. These standardized tests are inefficient for two reasons. Firstly, standard tests are based on mechanical, physical, chemical and thermal properties of a sand system that do not consider interaction between these properties, but sand casting processes are inherently thermo-mechanical, thermo-chemical and thermo-physical. Secondly, these tests can only detect large shifts in sand systems due to higher variability in their measured data. Because of this, the application of SPC using the results of standardized tests cannot detect subtle changes in sand systems.

In contrast, disc-shaped specimen tests developed at Western Michigan University collect data of independent as well as coupled thermal, mechanical, and physical properties of sand systems. In addition, these tests have shown their ability in reducing specimen-to-specimen and test-to-test variability. Therefore, in this research, these disc-shaped specimen tests are used to develop a SPC method for detecting a change in sand system by performing feature engineering on the data sets acquired from these tests.

The proposed approach to accomplish the goal is divided into three objectives. First objective is to determine that the disc-shaped specimen tests can differentiate changes in sand systems. To develop an effective SPC method, it is important to research the mentioned objective of this phase. In this research, several different sand systems are considered that represent changes in sand systems. Disc-shaped specimen tests are performed on disc-shaped specimens of these sand systems and test data are collected using current practice. Collected data are analyzed for their classification capability.

Second objective is to perform feature engineering on the data set acquired from disc-shaped specimen tests to detect a shift in sand systems. This step focuses on implementing SPC using feature/s of these test results to detect any shift in a sand system. Thermal distortion test which is one of the important disc-shaped specimen tests, produces time-series data for multiple variables. SPC method using these time-series data was considered in this phase and results suggests that SPC using principal component analysis can help better discriminate changes in sand systems.

Third objective of this research is to combine SPC method to casting quality. In this phase, a quality control framework is proposed that can be used to verify the casting quality. After detecting a change in sand system, foundry need to verify effect of that change on casting quality because not all process shifts reduce casting quality passed an acceptable limit. The quality control framework, in this phase, uses surface defect casting trial that uses disc-shaped specimens to validate casting quality and “qualify” a chemically bonded sand system. A sand system is deemed qualified if casting trials are free of a specific defect under given process parameters.

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BRIEF OUTLINE OF THE DISSERTATION

This dissertation document is organized into four chapters.

Chapter I – Discusses introduction and significance, disc-shaped specimen tests, literature review, gaps in literature and research objective

Chapter II – A decision tree based classification of sand systems to validate that disc-shaped specimen tests can differentiate changes in sand systems. This chapter is a published research paper in AFS Transactions, 18-035 (2018).

Chapter III – Statistical process control to detect a shift in a chemically bonded sand mold/core making process. The work documented in this chapter is a published research paper in AFS Transactions, 19-127 (2019).

Chapter IV – Chemically bonded sand mold/core qualification framework that combines statistical process control to quality of casting. The quality control framework is published in International Journal of Metalcasting, April 2018, Volume 12, Issue 2, pp-214-223.

Chapter V – Contributions and future work – This section discusses contribution of this dissertation in metal casting and foundry societies around the world and highlight recommendations for future work.

References – This section shows bibliography of material used as reference during the conducted research.

CHAPTER I

INTRODUCTION AND SIGNIFICANCE

The United States is the third largest supplier of castings in the world and metal casting industry is the sixth largest in the country according to American Foundry Society (2019). Metal castings are essential to majority of industries such as defense, automotive, construction, agriculture, aerospace, oil and gas, mining, railroad, transportation, and health care. Quality of castings is a major contributor to the success of these industries as well as foundries.

Casting quality and rejection rate are directly related to costs of foundry operations such as labor cost, energy cost, raw material cost etc. and may lead delay in delivery to customers. In addition, consumption of sand and its price are increasing. Metal casting industries use about 9% of the industrial sand for foundry purposes (Dolley, 2014). Figure 1 shows a visual representation of dramatic increase in unit price of sand and gravel based on data collected from Kelly and Matos (2016). According to Villioth (2014), sand is the second most widely consumed natural resource. According to Gibbs (2011), there are some concerns about shortage of sand in the future. It can be considered a responsibility of all industries in the world to minimize waste of sand. Foundries can minimize sand waste in several different ways. The leading and widely used way is to recycle or reuse sand. However, it is impossible to reclaim 100% sand due to inevitable losses in casting process as well as recycling process. Secondary and still under learning way to minimize waste of sand is to minimize sand related rejections in foundries by controlling sand system. If quality of castings is acceptable every time foundry pour molten metal into molds then indirectly, foundry is minimizing waste of sand.

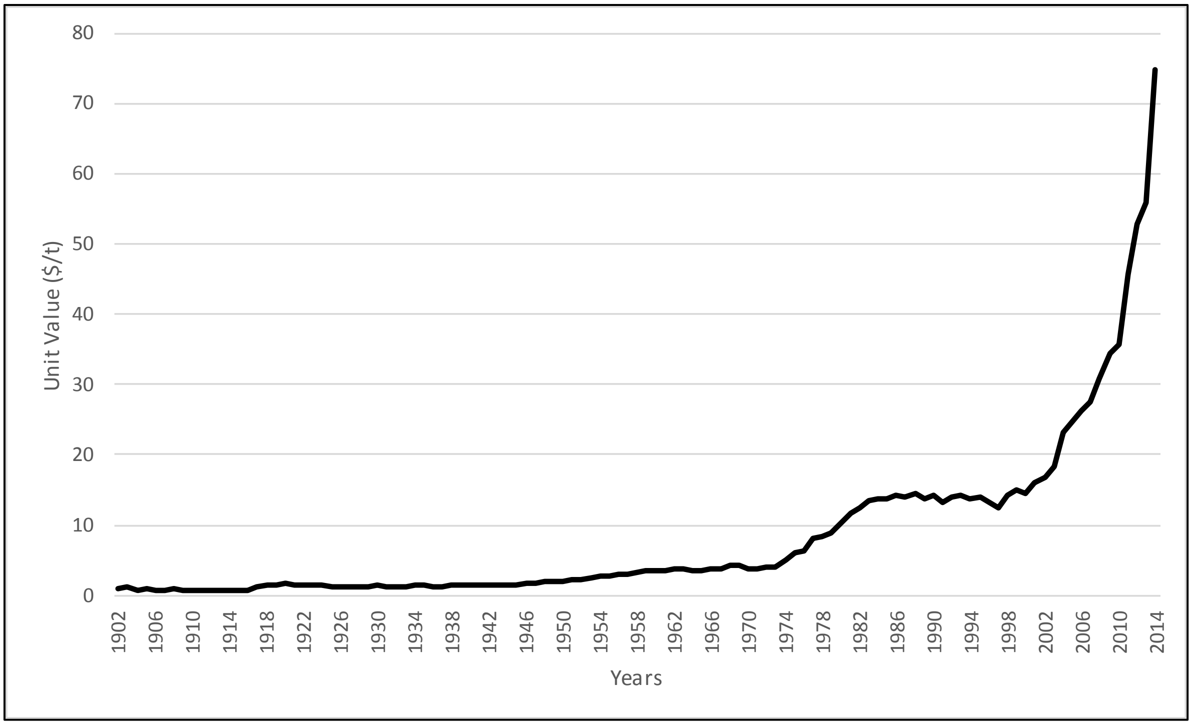


Figure 1. Unit Price of Sand and Gravel

Sand is majorly used either as a green sand or as a chemically bonded sand in foundries. Green sand is a mixture of sand, clay and moisture. Up to now, several practices have been identified to control green sand mold making process. These practices include sand testing, analysis of variance, linear regression, Taguchi method, simulation, particle physics etc. In the United States, green sand testing is majorly used for sand control and these tests can be prioritize according to the need of a foundry (DiSylvestro, 1998). Jacobson (2015) introduced a method of mass balance which calculates how much new clay should be added for a specific job. In addition, a software-based data driven modelling approach to control green sand has been evaluated by Patel et al. (2016) that provides rejections predictions based on historic data. Despite having many different approaches, foundries are still struggling to maintain the quality of green sand castings majorly because of dynamic nature of a green sand.

In contrast to green sand, chemically bonded sand uses chemical binder and catalyst to cure and harden a mold/core. There are different chemically bonded sand processes like hotbox, cold-box, no bake, injection transfer molding, 3D printing etc. Each of these processes have a specific binder(s) that can be used to make mold/core. Chemically bonded sand is widely used for manufacturing mold/core because of its high productivity and dimensional accuracy advantages over green sand. Quality of chemically bonded sand casting is highly sensitive to a sand system being used to make mold/core. When chemically bonded sand mold/core is exposed to molten metal, it can lead to casting defect if appropriate sand system is not being used. Therefore, it is important to identify assignable causes of changes in a sand system. Appropriate testing procedures that determine chemically bonded sand system properties can help determine this type of change in a sand system.

In the United States, the American Foundry Society (AFS) standardized sand tests are majorly used to monitor changes in a chemically bonded sand system. These tests are based on independent properties like physical, mechanical, chemical and thermal properties of a sand system but sand casting processes are inherently thermo-mechanical, thermo-chemical and thermo-physical. Foundry engineers have recognized that certain AFS standardized sand tests provide limited information regarding behavior of a sand system and this restricts engineers from controlling chemically bonded sand system and casting quality (Ramrattan, 2016). In addition, test such as hot tensile strength has high variability in their measured data (Stancliffe, 2006). Previous research results (Stancliffe, 2006 and Woods, 2018) shows that this test can only detect obvious uncommon changes in sand systems which restricts the effectiveness of statistical process control methods to monitor small changes in sand systems. This suggests that foundries need a new method to monitor chemically bonded sand systems that can help foundries to quickly detect small and large changes in sand systems.

Ramrattan (2016) have developed disc-shaped specimen tests for chemically bonded sand that use disc-shaped specimens. These tests have shown reduced variation across wide range of test results in previous study (Ramrattan at el, 2014). These tests are based on independent properties like mechanical, physical, and thermal as well as interactive characteristics such as thermo-mechanical, thermo-chemical and thermo-physical of a sand system (Iyer et al., 2001). Therefore, these disc-shaped specimen tests were considered in this dissertation to establish a quality control framework and monitor chemically bonded sand systems. It is a hope that analyzing results of these disc-shaped specimen tests, for variety of sand systems with engineered changes, will help develop an effective statistical process control method that can help quickly detect small as well as large changes in chemically bonded sand systems. Following section describes how these disc-shaped specimen tests are performed and data are collected at Western Michigan University (WMU).

Disc-Shaped Specimen Testing Procedures

Following are the disc-shaped specimen tests for chemically bonded sand systems that have been developed over 25 years of research efforts at WMU.

1. Specimen weight
2. Impact test
3. Hot permeability
4. Abrasion test
5. Thermal distortion test

6. Mass loss
7. Retained strength
8. Surface defect casting trial

These tests use disc-shaped specimen of 50 mm diameter. Figure 2 shows an illustration of a typical disc-shaped specimen. A nominal value of thickness is 8 mm. However, minimal section thickness in a mold/core will dictate disc-shaped specimen thickness.

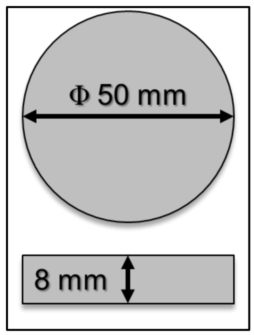


Figure 2. A Typical Disc-Shaped Specimen

There are several different processes for chemically bonded sand systems such as hotbox, cold-box, no bake, injection molding, 3D printing etc. Some of these processes require specialized tooling to make disc-shaped specimens. Though, it is advised to produce a disc-shaped specimen along with actual production of mold/core to include variation associated with manufacturing process of chemically bonded sand systems. The purpose and current practice for conducting these tests are discussed in following sections.

Specimen Weight

The disc-shaped specimen’s weight is recorded using a 0.01 g precision digital balance. The purpose of this measurement check is to detect specimen-to-specimen variability. Different chemically bonded sand processes, such as no-bake, phenolic urethane cold-box, hot-box etc., have variation in density of disc-shaped specimens which may affect other test results such as impact strength, permeability, TDT etc. Therefore, it is important to check density of disc-shaped specimens to verify the filling process of the specimens (that represent actual mold/core) is consistence in continuous production.

Impact Test

An impact test is performed on a disc-shaped specimen to measure the toughness of the sand specimens. Impact strengths relate to handling of the core/mold material after core/mold production and prior to pouring.

Equipment: A Tinius Olsen impact tester (Figure 3).

Procedure: The disc-shaped specimen is supported on its edge on a specimen holder on the impact testing machine (Figure 3). It is then subjected to impact energy by dropping a uniform load with a 2 mm thick rounded edge blade across its diameter. A load-cell electronically senses the specimen failure, digitally recording the results. The maximum energy to failure (Joules) is recorded.

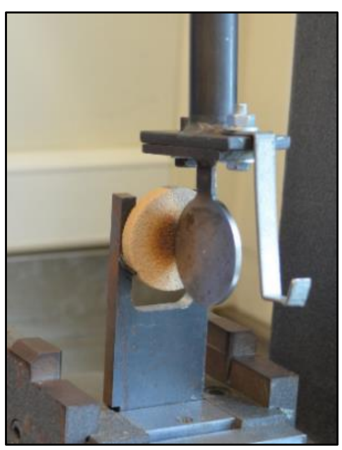


Figure 3. Disc-Shaped Specimen on Holder at Impact Tester

Hot Permeability

Permeability tests are performed to provide a measure of the specimen's venting characteristics. Permeability is a measure of gas flow through a porous media, such as a sand mold or core. The principle on which this instrument works can be defined as follows. The total discharge is equal to the product of the permeability of the medium, the cross-sectional area to flow, and the total pressure drop, all divided by the viscosity and the length over which the pressure drop is taking place.

The permeability of a sand mold or core is affected by several factors including the size, shape, distribution, and method of compaction of the sand in the mold or core box. Furthermore, permeability is directly affected by the quantity of resin in the sand.

Equipment: A Gerosa Simpson permeability tester (Figure 4). A specimen holder designed and fabricated for disc-shaped specimens (Figure 5).

Figure 4. Permeability Tester with Accessory Attached

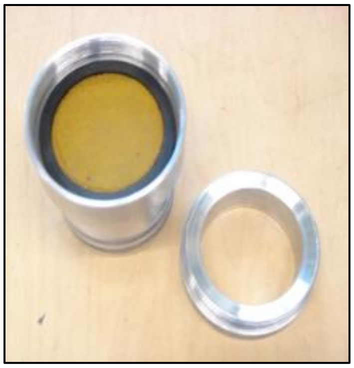


Figure 5. Specimen in Gasket within Holder Accessory

Permeability testing is not a standardized test for a chemically bonded sand system. The specimen holder (Figure 5) is designed and fabricated especially for holding a disc-shaped specimen. The permeability is measured at both ambient temperature and at elevated temperature and the permeability index is calculated.

Perm. Index = Hot Perm. - [(Ambient to Hot Perm. Range)/2]

Procedure: The specimen is secured into a holder (Figure 5), which was then fixed to the permeability tester. Then the test is started, and the permeability is measured. The test can be repeated with a 20 mm dia. hot surface (760°C) heating the center of the specimen as the hot permeability is measured (Figure 6).

Figure 6. Hot Permeability Set-Up

Abrasion Test

Abrasion resistance defines the property of a material surface to resist wear while in contact with another material. The determination of the abrasion/wear resistance of a disc-shaped specimen plays a vital role in the estimation of effect on sand mold/core surface due to handling procedures. This test method encompasses ability to compare strength for different sand specimens against scratch or wear caused by handling.

Equipment: Teledyne Standard Abrasion Tester Model 503 equipped with a custom sample holder for disc specimens (Figure 7).

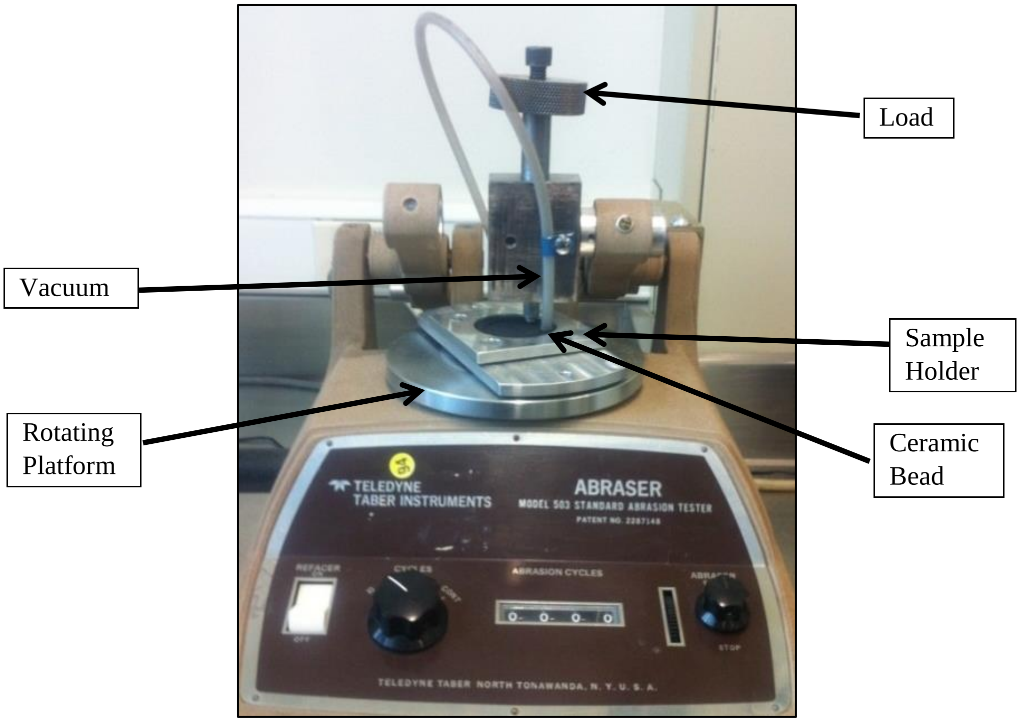


Figure 7. Abrasion Tester

Procedure: The 50 mm dia. x 8 mm thick disc-shaped specimens are weighed and secured onto the sample holder using four screws, one at each corner. The sample holder is mounted onto the abrasion tester with a ceramic bead pressing against the specimen surface perpendicularly as shown in Figure 7. A desired load is applied onto the ceramic bead by mounting corresponding circular weights on top of the abrading assembly. The specimen is then rotated in clockwise direction maintaining a constant rotational speed for a desired number of cycles/rotations. To ensure the proper contact between the ceramic bead and sand specimen surface, a vacuum is applied continuously to pull any loose sand particles during the test run. Reweighing the specimen and calculating the weight loss or percent weight loss then determined the abrasion/wear resistance of the specimen surface.

Usually, the sand specimens are tested for 10 cycles/rotations with a load of 250 g on the ceramic bead and thereafter calculating weight loss and percent weight loss as a result. However, these parameters can be adjusted to represent the rigors of the casting process.

Thermal Distortion Test (TDT)

TDT has the capability to mimic heat and pressures that sand systems will experience from molten metal filling and solidifying in a mold. The word “mimic” must be emphasized since molten metal has never been used with the TDT, and there is no exact replication 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 8). Holding the temperature of the hot surface constant during testing simulates the mass of molten metal. Several instruments, controllers, mechanical devices, and a computer are used to record data and accomplish all the functionality of the device.

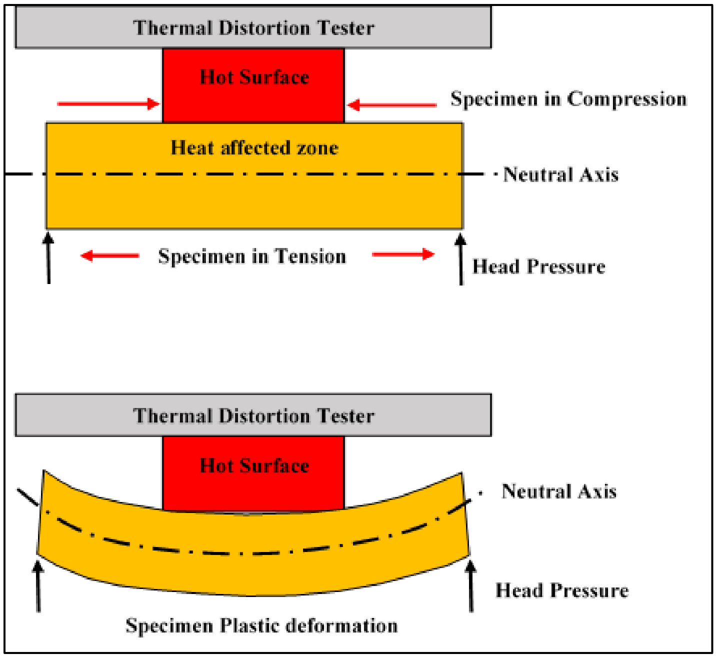


Figure 8. TDT Stresses on Specimen

A disc-shaped specimen receives a load about the circumference of one side as the other side is pressed onto a heated metal surface. 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. To prevent any shear forces from acting on the specimen surface in contact with the heater, a two-axis gimbal is used (Figure 9) for self-leveling and symmetric orientation of the specimen.

To provide temperatures that simulate molten metal, a super alloy tipped heater with other heating elements are used. The utilization of a large heated mass has the purpose of assuring that the 90-second test is conducted with as constant of a temperature as possible. The heater is enclosed in insulation to direct the heat to the specimen.

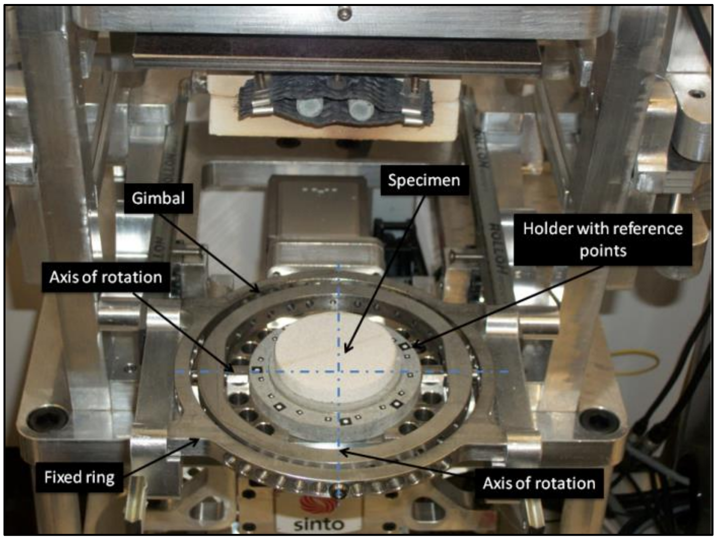


Figure 9. Gimbal Assembly

Equipment: This version of the TDT uses a variety of devices to collect data and control the heating process. The data that is acquired during each test is radial and longitudinal deflection, temperature at the hot surface and backside of specimen, with respect to time.

Procedure: To operate the TDT (Figure 10) the temperature control can be adjusted up to 1200°C (2192°F) to represent gray cast iron/sand mold interface.

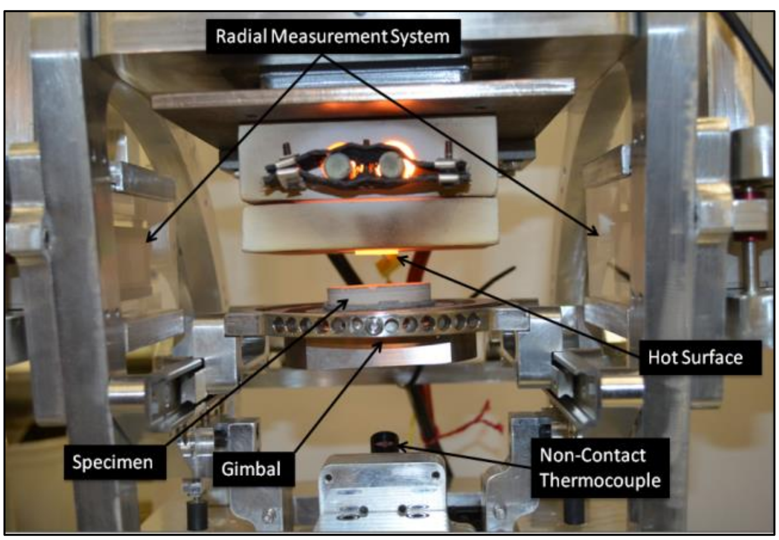


Figure 10. Thermal Distortion Tester (TDT)

The disc-shaped specimen is mounted onto a pivoting gimbal holder (Figure 9 and Figure 10) and the specimen is automatically raised to achieve a symmetrical contact with the 2 cm (0.787 in.) dia. hot surface. Upon contact linear voltage displacement transducer is engaged at this point, which simultaneously engages a laser to measure the distortion in longitudinal and radial directions. The distortions/temperature versus time curves are generated using the integrated data acquisition system. The TDTs are performed over a 90-second interval, being based upon solidification simulation results for medium size cast iron castings. Data are collected at 10 Hz by the data acquisition system for longitudinal distortion, radial distortion, and backside temperature. These data are usually plotted in graphs as shown in Figure 11 and Figure 12.

A system is considered thermally stable (no displacement longitudinally and radially) if the Thermal Distortion Curve (TDC) is a horizontal line with the origin. Figure 11 shows that longitudinal distortion (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.

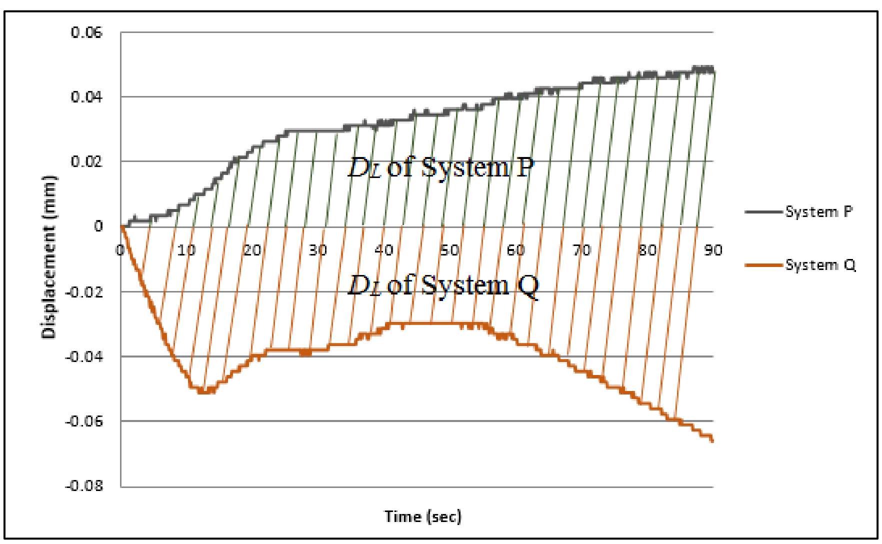


Figure 11. Measure of a Longitudinal Distortion

Figure 12 shows that radial distortion (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.

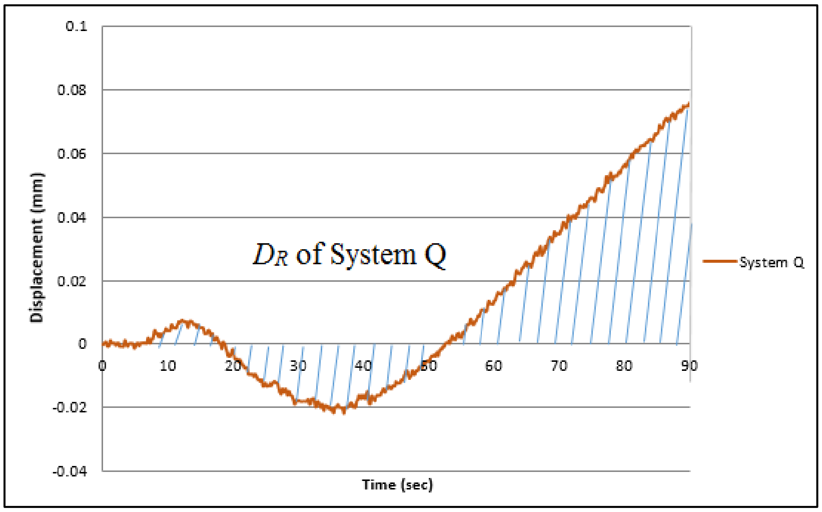


Figure 12. Measure of a Radial Distortion

The D_R indicates outward expansion of the disc-shaped specimen. For 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, total distortion (T_D) is addition of longitudinal distortion (D_L) and radial distortion (D_R).

<u>Mass Loss</u>

Prior to TDT, each specimen is weighed. Following TDT the surface of the specimen is blown with 2-psi (0.014 MPa) air pressure to remove any loose sand grains. The specimens are reweighed, and the percent change in mass is recorded. Then the specimens are visually examined for signs of thermally induced cracking (veining) of the surface, loss of sand where contact is made with the hot surface, and any other discolorations or visual observations. If the core/mold media breaks down, this 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.

Retained Strength

After calculating mass loss, an impact test is performed on the specimen to measure its retained strength after exposure to an elevated testing (TDT). This relates to the energy required to shakeout the mold/core. Shakeout of used sand molds and cores affects productivity in foundries. After pouring molten metal in to molds and solidification of metal, it would be great for foundries if molds/cores shakeout easily without much effort, but, some sand systems requires more vigorous shakeout which may affect efficiency of production.

Surface Defect Casting Trial

Casting trial involve molten metal that is used in actual casting production while all the above tests are performed in a process monitoring laboratory and does not involve molten metal used in actual casting process. The purpose of this test is to identify the effect of super heat, metallostatic head and external load on the disc-shaped specimens to determine what combination may cause casting surface defect. This test can be used to compare the casting results of different sand systems.

In surface defect casting trial, up to twelve different sand systems can be used in the form of disc-shaped core specimens. The specimens can be compared using an experimental pattern to perform a casting trial where various alloys can be poured from a certain head height at a specified superheat temperature. Molds can be developed so that molten metal could be delivered to twelve disc-shaped specimens simultaneously.

The drag molds with twelve specimens set on core-prints is shown in Figure 13. A pouring sleeve of certain height can be affixed to the cope as a sprue to deliver the metallostatic head. A computer aided design (CAD) representation of the casting trial (surface defect model) is shown in Figure 14.

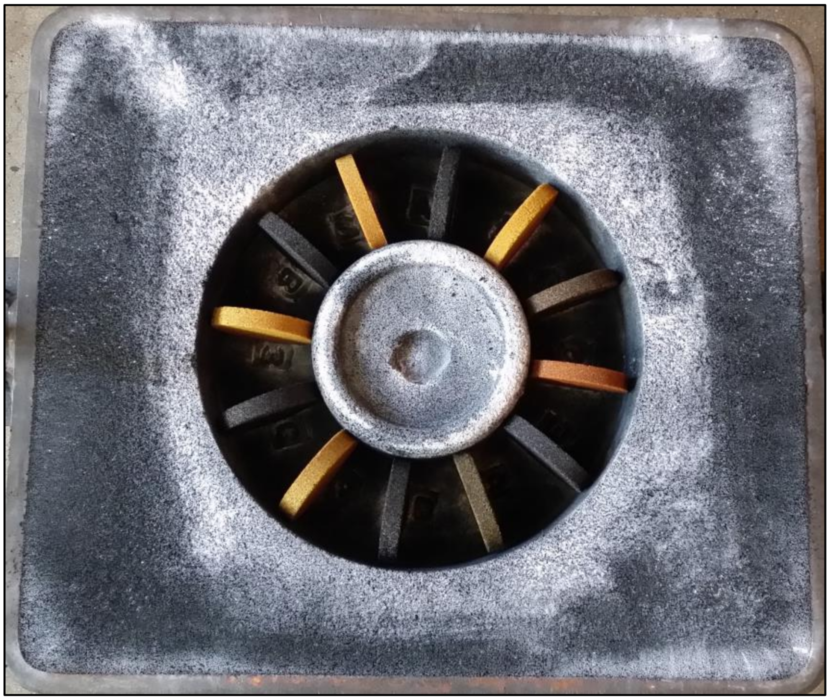


Figure 13. Drag Mold with Specimens

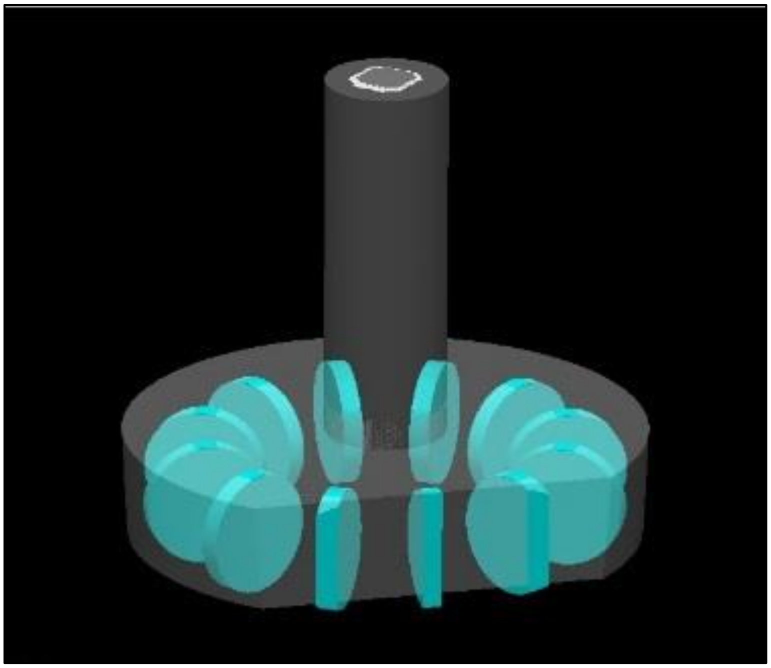


Figure 14. A CAD Representation for the Surface Defect Model

Literature Review

Every chemically bonded sand casting foundry uses sand system that is appropriate for the metal chemistry, pouring head height, and complexity of parts. However, when changes occur in a sand system such as percentage binder level, additives level, sand grain fineness and/or shape of sand grain etc. foundries may end up with higher rejection or worst casting quality. Following section discusses relation between casting defect and sand system.

Relation between Casting Defects and Sand System

Rejections in foundries can occur due to many of the several factors such as (1) improper design of pattern, tool, and gating system, (2) improper melting and pouring practices, (3) improper metal composition, (4) mold/core making raw materials (sand, binder and other additives) and process parameters (Pribulová et al., 2013). Foundries have better means to handle the first three factors. Pattern, tooling, and gating designs can be optimized by simulation software. Nimbulkar and Dalu (2016) used solidification simulation software to optimize the gating/riser system design. Education and training can help overcome improper melting and pouring practices. Chatrad et al. (2016) studied influencing melting and pouring parameters like melting of the metals, alloy agents, pouring temperature, pouring process and pouring time, impurities present in the ladle, etc. and suggested optimized parameters that minimize casting defects for grey cast iron. A change in a metal composition can be detected by spectrographic atomic absorption or x-ray fluorescence analysis of molten metal or by mechanical testing on metal like hardness test, tensile strength or impact test. However, the only factor that majority of foundries are lacking is to monitor changes in chemically bonded sand systems.

Chemical binders used in chemically bonded sand mold/core can cause many casting defects like erosion, veining, scabbing, penetration, blowhole, porosity, hot tears, etc. if above mentioned factors are inappropriate or non-optimal (Campbell et al., 2014). Among these defects many have known causes and that have known straightforward remedy. However, other defects may result from a combination of factors unknown to foundry engineers, which may make preventive measures to be more ambiguous. In practice, foundry engineers are aware of specific defects they are getting during day to day production at their respective foundries. Some of these defects appear without warning and disappears without any information of its original cause. Precautions that are more specific can be taken in those cases where there is a known vulnerability to a specific defect. A strong understanding of major sources of variations can above all, minimize defects (Beeley, 2001) and standardization of all aspects of production offers the best protection against such dilemmas. But due to overly complex nature of casting process, it is challenging to standardize all sources of variations, as for example sand. There might be slight differences in sand grains excavated from different places, or different heights etc. This requires qualifying sand system to confirm that these variations will not deteriorate casting quality.

Khandelwal and Ravi (2016) studied the effect of sand grain size, binder percentage and curing time on mechanical properties of a chemically bonded sand system using Taguchi's design of experiments. In this study, effect of changes in sand system characteristics was studied through laboratory experiments. This study shows that certain level of sand system characteristics like grain fineness number (GFN), binder percentage and curing time are favorable for achieving desired properties of a sand system. However, no attempt was being made to relate the effect of these changes on casting surface quality and/or rejection. It is important for foundries to recognize how these changes in a sand system will affect the casting quality and rejections.

Shailesh et al. (2014) investigated effect of processing parameters on mechanical properties using Taguchi's design of experiments. In another study, Kassie and Assfaw (2013) attempted to optimize process parameters by performing statistical analysis on experiments designed by Taguchi's factorial experiment method. They used experimental casting trials to compare the quality of casting surface. Nevertheless, these designed experiments may not always represent wide variety of changes in a process.

Thiel and Ravi (2014) investigated experimental step cone casting to identify possible veining defects associated with sand systems. This casting is heavy and are costly to do experimental study. In addition, the core/mold used in this casting may not represent actual mold/core making process. On the other hand, the casting trial mentioned in testing procedures are comparatively less costly and easy to conduct. If foundries can produce a disc-shaped specimen with the production of actual mold/core, the specimen used for casting trial will represents actual mold/core making process.

Differentiating between Sand Systems

Foundry engineers know that current AFS standard mechanical properties tests such as immediate tensile strength does not differentiate between several subtle changes as shown in Stancliffe (2006). A slight difference in tensile strength can be observed if test specimens are tested after 24 hours of being produced (Stancliffe, 2006). 24 hours is a long time and foundries cannot afford to wait that long to identify unintended differences in a sand system that may cause higher rejections. Otherwise, they will keep producing scrap until they know that a process shift has occurred. So, foundries require a set of tests that can be used to identify changes in a sand system as soon as the specimens are being made. It is also important to mention that these tests must differentiate between design changes as well as assignable changes in a sand system. Designed changes are caused by known changes such as sand type, binder type, process type etc. while assignable changes are due to subtle changes in a sand binder such as sand grain size, sand screen distribution, binder level, etc. which could be caused because of batch-to-batch variability in raw material and/or alterations in process parameters.

Disc-shaped specimen tests discussed earlier can be used as soon as the specimens are made. These tests use a simple shape (disc-shape) specimen that helps to achieve lower measurement variability and it is shown in previous study (Ramrattan et al., 2016b). In recent years, several research studies have been completed to qualify chemically bonded sand system based on the results of these disc-shaped specimen tests. In one study conducted by Ramrattan et al. (2016a), properties and characteristics of six different silica sands used in 3D printing were evaluated using the disc-shaped specimen tests. Specimens were made using 3D printing with the same type and level of binder used for all sands and disc-shaped specimen tests were performed on each of these six sand specimens. Among these six different sands, one sand system was identified as a favorable sand system for an Aluminum casting and the results were successful in actual practice.

In another study conducted by Ramrattan et al. (2016b), three different sand systems- shell, phenolic urethane cold-box (PUCB) and injection transfer molded (Lytecore) binder systems were compared under same test parameters to evaluate newly developed eco-friendly high production injection molded core binder system for aluminum. Results suggest that injection transfer molded sand system is less vulnerable to penetration defect compared to other two sand systems and produces much higher as cast surface finish. These results were also successful in actual casting practice.

Former research efforts from Ramrattan et al. (2016a and 2016b) have shown that the disc-shaped specimen tests have differentiated between several different sand systems. Process type, sand type, and binder type represents designed differences in sand systems while sand grain shape, GFN, and binder level, etc. represents assignable differences in sand systems. If these changes in sand systems can be categorized by the mentioned disc-shape specimen tests, then these test results can be used to identify, create and extract key features for developing a statistical process control method to monitor these types of changes in chemically bonded sand systems.

Statistical Process Control

Statistical process control (SPC) tools and concepts have frequently applied and have become very important in manufacturing and process industries. SPC has two goals. (1) Detect shift by monitoring product and/or process variables, and (2) recover from the shift if the shift is bad or maintain the shift if it is a good shift. Individuals based on knowledge and experience make all the decisions to recover based on results of SPC. It is expected that the process operates under a state of statistical control which is assumed to exist if process whose measure under evaluation remains in a state of statistical control and the only source of variation is "common cause" variation, that is, variation which affects the process all the time and is essentially unavoidable within the current process (Montgomery, 2008).

SPC charts (also known as control charts) such as Shewhart, cumulative sums (CUSUMs) or exponentially weighted moving average (EWMA) chars are used to detect the occurrence of any event having a "special" or "assignable" cause. By finding assignable causes, long-term improvements in the process and in product quality can be achieved by eliminating the causes or improving the process or its operating procedures. These are admirable at demonstrating when process data that contains variation. This section does not cover a full review of SPC. Readers interested in more detailed review of SPC may refer Woodall and Montgomery (1999).

With respect to research in casting, a study conducted by Stancliffe (2006) and Woods (2018) show that standardized test like immediate tensile strength does not differentiate subtle differences in sand systems. SPC using these standardized tests data is not capable to identify a shift in a sand system because of the high variability in the test results. This clearly shows that foundries require a new SPC methodology that uses right data (hopefully from disc-shaped specimen tests) to differentiate changes in chemically bonded sand systems.

Control Charts: The philosophy of SPC, is to use data to continually improve quality by collecting, organizing and interpreting the wide variety of available information. The major statistical tool used to measure, understand and control the variables is the control chart. The standard X-bar chart has been widely applied in many industries due to its versatility and easiness for use (Jensen et al., 2006). Within the automotive manufacturing industry, the standard control chart has been applied for very long time. Methods for control charting have been recommended by the Automotive Industries Association Group (AIAG) in its reference manual SPC for automotive suppliers in the USA. It is recommended to use either CUSUMs or EWMA chart to detect small shift in a process.

If two or more quality characteristics are to be monitored independently in a univariate approach, it could lead to misleading results. In such cases, multivariate control charts can be used. Multivariate control charts rely on correlation between different test results. A study conducted by Prabhu and Runger (1997) suggested recommendations for selecting parameters for multivariate exponentially weighted moving average (MEWMA) that can be used to monitor two or more correlated process characteristics in an exponentially weighted control chart at the same time. Hotelling's T^2 control chart is customarily used as the control chart for multivariate statistical process control analysis. Similar methods may be used for developing multivariate control charts for chemically bonded sand systems if needed.

Except specimen weight test, all other disc-shaped specimen tests are destructive tests. Several research studies have been conducted to determine the correlation of destructive tests. In a study conducted by Evans et al. (1984), correlation between two mechanical properties (bending strength and tensile strength) of a piece of lumber was estimated using proof loading method. Proof loading refers to a scheme where one tries to break only weakest pieces in population using one test and use unbroken pieces for the other test. In another study by Steiner and Wesolowsky (1995) suggested two simple proof load testing procedures to estimate correlation between two variables that can individually obtained by destructive tests. Similar procedures may be useful to identify correlation between any of the disc-shaped specimen test results if two or more tests are used to develop SPC method.

There are two distinct phases of control charts. Phase I control charts are used to determine whether historical data indicates a stable process or not and to estimate process parameters, while phase II consists monitoring future observations using control limits calculated from phase I. In case, when sufficiently large samples are unavailable for phase I control chart, self-starting control charts is an option. Li et al. (2008) proposed a self-starting control chart based on likelihood ratio test and EWMA procedure for monitoring process mean and variance simultaneously when process parameters are unknown. Zou et al. (2007) and McClurg (2016) have also proposed a self-starting statistical control chart methodology for linear profiles or trend. Self-starting control charts are useful when production is slow or when the cost of early out-of-control production is high. Majority of foundries in the U.S. are continuously manufacturing casting in highly automated working environment which usually have high production rates therefore, application of this strategy may not be appropriate for majority of foundries. However, self-starting control chart may remain an option for foundries which make castings at slow rate.

<u>Profile Monitoring:</u> The concept of profile monitoring can be applied to the distortion curves generated in TDT. Several different models of profile monitoring such as simple linear regression, multiple and polynomial regression, non-linear regression, and wavelets etc. are acknowledged by Woodall (2007). To monitor the slopes of relationships, Chang and Gan (2006) proposed some Shewhart control charts for monitoring the slopes of relationships between two or more measurement processes to assure their accuracy.

In metal casting, McIntyre and Strobl (1998) have introduced the concept of achieving process control using hot distortion curves almost two decades ago. Hot distortion curves require visual observations to determine a change in the behavior of a sand system. Using that approach for SPC will create a lot of false alarm regarding the process being out of control. One can adjust control chart parameters to avoid this but, it will reduce its sensitivity to detect small shifts in a process. In addition, it is difficult for foundry engineer to differentiate changes in curve slopes, valleys, and peaks for a given sand system. Only qualified researcher has the knowledge to interpret and compare curves.

On the other hand, results of TDT is collected in numeral form to represent distortion (Ramrattan et al. 2016a and 2016b). Therefore, the use of the SPC using TDT may open a new opportunity for foundries to monitor chemically bonded sand system in a better way. If disc-shaped specimen test results can be used to differentiate excessive variation in normal process and raw material, then it would promote these tests from the ranks of a research practice to tests that can be used to collect data for quality control.

Gaps in Literature

Until now, foundries were trying to develop a SPC for a chemically bonded sand using standardized tests of sand system. These standardized tests are inefficient to differentiate between small changes in a sand system for two reasons. Firstly, standard tests are based on mechanical, physical, chemical and thermal properties of a sand system that does not consider interaction between these properties while sand casting processes are inherently thermo-mechanical, thermo-chemical and thermo-physical. Secondly, these tests can only detect large shifts in sand systems due to higher variability in their measured data. Therefore, implementation of SPC for chemically bonded sand was limited. For foundries, there is a need to look for alternative tests that can give more information than these standardized tests. The disc-shaped specimen tests have shown reduced variation across wide range of test results. Yet, to test ability of these disc-shaped specimen tests and develop a methodology to qualify and administer chemically bonded sand using these tests require more research.

When sand, binder or other additives supplier ship a new batch of raw materials, there is a chance of batch-to-batch variability. These types of changes in a sand system are difficult to identify from foundry's point of view, as foundry may not know what exactly the change in raw material is. Under this condition, foundries continue producing casting assuming that there is no change in raw materials and may end up with higher rejections because their current standardized tests are not capable to identify any change. In addition, when foundries and sand binder suppliers change their raw material source based on several different factors such as cost, proximity, deleterious health related issues, and ecofriendly benefits etc., foundries may get higher rejections if the new sand system is not qualified. Currently foundries need a method to identify an unknown change in a chemically bonded sand mold/core making process that can occur due to raw materials and process parameters before it causes higher rejection down the production line.

In addition, foundries are anxious to try newly developed sand systems like inorganic binders, injection molded technology, aeration technology etc. They are afraid because they do not know how these new technologies will affect the casting quality or rejections. Currently foundries need to understand and compare this type of new technology with the existing technology and recognize their effect on casting quality. Foundries have no way to confirm effect of this newly developed sand systems on casting quality except to try it in production and find out.

This research aims to propose method(s) to detect a shift in a chemically bonded sand system and methodology to qualify a chemically bonded sand system for a specific defect using disc-shaped specimen tests. These tests had been developed for over twenty-five years of research efforts at WMU. In contrast to higher variability of measured data for the standardized tests, disc-shaped specimen tests have shown reduced variability across wide range of test results. Therefore, to develop an effective SPC method for chemically bonded sand systems, the disc-shaped specimen tests were considered in this dissertation.

In this dissertation, it will be verified that the disc-shaped specimen tests are able to discriminate large as well as small changes in sand systems. This research aims to focus on establishing a new quality control framework that combine a SPC approach to casting quality using disc-shaped specimen tests. It is hoped that this research provides enough evidence to motivate AFS to standardize these disc-shaped specimen tests that can help all foundries in the world to better detect a change in chemically bonded sand systems.

As a part of this dissertation a SPC method will be developed that a foundry can use to detect wide range of process shift in chemically bonded sands. Furthermore, a quality control framework can help to verify the effect of change in sand system on casting quality. This can help foundries to quickly detect a change in sand system and take preventive measures in case of that change will cause higher rejections down the production line. Use of quality control framework will be demonstrated by a case study that will represent a real-world scenario of a change in sand system.

Research Objective

The goal of this dissertation is to establish a new quality control framework that combines a statistical process control (SPC) approach to casting quality for chemically bonded sand systems used in foundries. Figure 15 shows the concept of the new quality control framework.

The quality control framework is based on monitoring chemically bonded sand systems using SPC. Foundry needs to collect sand system characterizations such as GFN, loss on ignition (LOI), and sand grain shape etc. and needs to perform disc-shaped specimen tests on the specimens of sand systems during continuous production. If a change in chemically bonded sand system is detected then a casting trial need to be performed for a specific casting defect such as surface defect, erosion, distortion, etc. whichever is the most concerning to a foundry. If casting quality is not acceptable then it is recommended to make changes in sand system to improve casting quality.

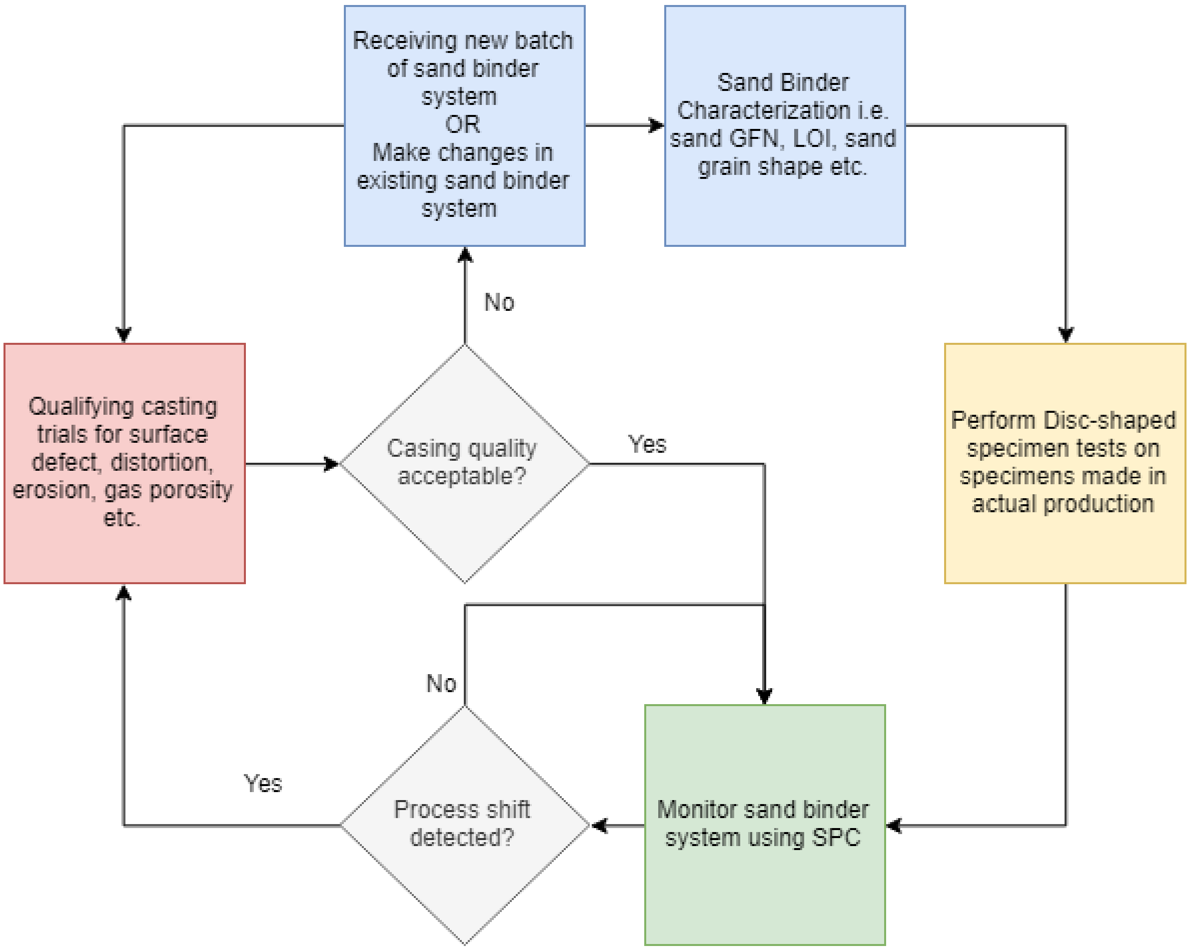


Figure 15. Concept of Quality Control Framework

The proposed approach to accomplish the dissertation goal is divided into three objectives. Each of these objectives are covered in separate chapters in this dissertation (Chapter II to IV).

1. Determine classification capability of disc-shaped specimen tests to discriminate between changes in sand systems
2. Develop statistical process control method to detect a change in sand systems
3. Propose and demonstrate a quality control framework that combines SPC to casting quality.

First objective is to determine that the disc-shaped specimen tests can differentiate large as well as small changes in sand systems. In working foundries, changes in sand systems may occur from designed changes and/or assignable causes. Designed changes occur when foundry engineer changes sand system parameters in foundries such as sand type, binder type, process type etc. while assignable causes are due to unintended changes in a sand binder such as sand grain size, sand screen distribution, binder level, etc. which could be caused by process variations and/or batch-to-batch variability in raw material. For this research, several different sand systems need to be considered that represents designed as well as assignable changes in sand systems. Disc-shaped specimen tests need to be performed on disc-shaped specimens of these sand systems. Test data of the disc-shaped specimen tests should be analyzed for classification capability.

Second objective is to perform feature engineering on the data set acquired from disc-shaped specimen tests to detect a shift in sand systems. This step focuses on identifying, creating and extracting features to implement SPC using disc-shaped specimen test results. Sensitivity of disc-shaped specimen tests may vary for different types of process shift in sand systems. To develop an efficient SPC method, it is essential that features extracted from the data set attained from disc-shaped specimen tests are sensitive to detect wide variety of process shifts. Sand systems with subtle differences need to be considered in this phase to develop an efficient SPC method to quickly detect a shift in chemically bonded sand systems.

Third objective of this research is to combine SPC method to casting quality. In this phase, a quality control framework is recommended that can be used to verify the casting quality and/or minimize rejections. After detecting a change in sand system, foundry need to verify effect of that change on casting quality because not all process shifts reduce casting quality passed an acceptable limit. In this phase, the idea is to use a casting trial that incorporates disc-shaped specimens to validate casting quality and "qualify" a chemically bonded sand system. A sand system is deemed qualified if a set of casting trials are free of (or contain an acceptable amount of) a specific defect under given process parameters.

CHAPTER II

CLASSIFICATION OF SAND SYSTEMS

Introduction

Chemically bonded sand molds and cores are widely used to produce near net shape castings (Campbell, 2000). Quality losses from casting defects are a major concern for the casting industry. Quality losses can be attributed to several different factors such as improper design of pattern, tool, and gating system, improper melting and pouring practices, improper metal composition, changes in mold/core making raw materials (sand, binder and other additives) and process parameters etc. (Pribulová et al., 2013). The defects caused by some of these factors can be reduced. Pattern, tooling, and gating designs can be optimized by solidification simulation software. Education and training can help overcome improper melting and pouring practices. A change in a metal composition can be detected by spectrographic atomic absorption or x-ray fluorescence analysis of molten metal or by mechanical testing on metal like hardness test, tensile strength or impact test. Unfortunately, it has been a challenge for foundries to identify changes in sand systems that may result in casting quality losses.

It has been shown in the literature that standardized sand tests exhibit significant levels of specimen-to-specimen and test-to-test variability (Stancliffe, 2006 and Ramrattan et al., 2014). Therefore, the use of standardized tests as the basis for a quality control system will be only be able to detect obvious uncommon changes in a sand system and will be insensitive to small frequent process changes. As for example, immediate tensile strength measurements using dogbone shape specimens were unable to differentiate between sand systems that had sands from different sources (Stancliffe, 2006). To quickly identify any change in a sand system that might affect casting quality requires a new approach to quality control for chemically bonded sand systems.

Background

Western Michigan University (WMU) has used a simple disc-shaped specimen, 50 mm diameter, 8 mm thick, as a foundry test specimen for twenty-five years. It is presumed that the use of a simple specimen geometry is a key factor in reducing the variability of sand systems tests (Ramrattan et al., 2014). Specifically, these specimens have shown reduced measurement variability across a wide range of disc-shaped specimen tests for chemically bonded sands, namely; specimen weight, abrasion, impact, hot-permeability, and thermal distortion. Achieved reduction in standard deviation for these disc-shaped specimen tests were published in previous AFS research paper (Ramrattan et al., 2014). In addition, several casting trials that use the same disc-shaped specimen have been used to complement these disc-shaped specimen tests to establish a link between sand system quality metrics and defects, such as; veining/penetration, gas, erosion or distortion at a specimen/metal interface (Ramrattan et al., 2011).

Recently, a new quality control framework that incorporates casting trials to “qualify” a sand system has been developed (Ramrattan et al., 2017). A sand system is said to be qualified if a set of casting trials are free of (or contain an acceptable amount of) a specific defect. Once a sand system is qualified, statistical process control (SPC) is implemented to detect shifts in the sand system by means of disc-shaped specimen tests. If the SPC system detects a shift in the sand system, this could indicate that the sand system may no longer be qualified. This quality control framework relies upon the ability of disc-shaped specimen test results to differentiate between different sand systems.

Purpose

The objective of this phase of research is to check if the disc-shaped specimen tests can differentiate between sand systems with some differences in them that might affect casting quality. A sand system can be characterized by several factors; such as: 1) Process type: (3D printed, hotbox, etc.), 2) Sand type (silica, lake, etc.), 3) Sand grain shape (angular, spherical, etc.), 4) Grain Fineness Number (GFN) and Number of screen distribution, 5) Binder type (furan, phenolic urethane etc.), and 6) Binder level (%) . It is believed that any change in these characteristics will affect casting quality. If one can detect these types of changes through laboratory testing, it would be beneficial for foundries to perform these testing to monitor their sand molding process. To ensure the results of this research are applicable to practice, the sand systems used in this study are commonly used in today's casting industry.

Methodology

The approach to achieve the objective consists of three major tasks:

1. Characterizing sand systems.
2. Conducting disc-shaped specimen tests and collecting test results.
3. Developing a classification model from the test results.

Sand Systems

Nine different sand systems which collectively represent changes were considered for the study. The characterization of these sand systems in terms of process type, sand type, sand grain shape, binder type, sand size (AFS-GFN), sand screen distribution, and binder level are also shown in Table 1.

Table 1. Sand System Characteristics - Classification Study

Class No.	Process type	Sand type	Sand shape	Binder type	Sand size (AFS-GFN)	Sand screen distribution	Binder level (%)
1	3D	Silica	Sub-angular	Furan	80	2	1.2
2	3D	Silica	Angular	Furan	80	3	1.2
3	Hotbox	Silica	Sub-angular	Shell	42	3	2.15
4	Hotbox	Lake	Angular	Shell	42	3	2.15
5	Hotbox	Silica	Sub-angular	Shell	42	3	1.05
6	Hotbox	Ceramic	Round	Shell	72	3	1.85
7	Injection molding	Ceramic	Round	Lytecore	72	3	0.5
8	Cold-box	Silica	Sub-angular	PUCB1	60	3	0.6
9	Cold-box	Silica	Sub-angular	PUCB2	60	3	0.6

Specimens of first and second sand system (Table 1) were made by 3D printing process and shipped to Western Michigan University (WMU) in a secure package. Both systems consist silica sand and same furan binder targeted at 1.2% based on sand. The only difference between these systems is the shape of the sand and sand screen distribution. Sand grain is more angular and screen distribution is larger for sand system 2 compared to system 1. System 3, 4, 5, and 6 are made up at WMU using hotbox (resin-coated shell) process. System 3and 5 has silica sand (42 GFN) while system 4 and 6 has lake (42 GFN) and ceramic sand (72 GFN) respectively. Ceramic sand is round while silica sand is sub-angular and lake sand is angular. System 3 and 4 have similar binder level while system 5 and 6 have binder level 1.05% and 1.85% respectively. System 7 has same sand as system 6 but it has different sand preparation process known as injection molding. These specimens were made and shipped from Japan. System 8 and 9 are made up using PUCB process. Both systems have similar sand type, sand shape, sand size and sand screen distribution, and binder level. The only difference is the binder supplier is different. These specimens were supplied from a customer whose anonymity is protected.

Disc-Shaped Specimen Tests

Disc-shaped specimen tests namely, specimen weight, hot permeability, impact test, abrasion test, thermal distortion test (TDT), mass loss and retained strength were performed on these nine sand systems using current practices. The results in terms of specimen weight (g), permeability and hot permeability (#), impact strength (J), abrasion loss (%), TDT mass loss (%), distortion (longitudinal, radial and total in mm*sec) were collected. The detailed procedure of these tests can be found in previous research study (Ramrattan et al., 2016b). It is important to mention that hot-permeability, impact test, abrasion test and retained strength are destructive test. In addition, retained strength is performed on the specimen which has been used for TDT. Specimen weight represents average weight of four specimens used for these tests. Fifteen data points for each of the eleven classes (total 135 data points) were collected. A data point consists one observation of all disc-shaped specimen test results. In other words, four disc-shaped specimens were tested to collect a single data point. (Note: All specimens were tested in laboratory conditions. Ambient conditions were controlled: temperature at 20 ± 1°C and relative humidity at 50 ± 2%).

Classification

Classification is a process of classifying objects according to their characteristics (attributes). Classification models are developed by training the model with a set of objects with known attribute data and known classes. The model is then used to classify new objects (objects with unknown classes) by their attributes. Several classification modeling approaches exist; such as, decision trees, Bayesian networks, neural networks, support vector machines, etc. (Voznica and Viana, 2007). For this paper, decision trees are implemented as they are one of the most widely used and simplest to implemented classification techniques in data mining and machine learning (Rokach et al., 2008). To enhance the performance (accuracy) of a decision tree this paper uses a random forest decision tree.

Random Forest - Decision Tree: A decision tree is a flowchart-like tree structure that is used as a classification method for decision support and machine learning process. Decision tree is applicable for investigative knowledge discovery because it does not require any special knowledge or parameter setting for its creation. Structure of decision tree is shown in Figure 16. Decision tree has three types of nodes: a root node, internal nodes and leaf or terminal nodes. The topmost node in a tree is the root node. Each internal node (non-leaf node) denotes a test on an attribute and each branch represents an outcome of the test, and each leaf node (or terminal node) holds a class label (Han et al., 2011).

Input of the decision tree algorithm are mentioned below (Han et al., 2011).

1. Input database, D, which is a set of training tuples and their associated class labels;
2. List of attributes, the set of contestant attributes;
3. Attribute selection method,

A procedure to determine the splitting criterion that “best” partitions the data tuples into individual classes. This criterion consists of a splitting attribute and, possibly, either a split-point or splitting subset. In addition, a decision tree selects an attribute using single column of data, therefore, correlation between different columns does not affect the results.

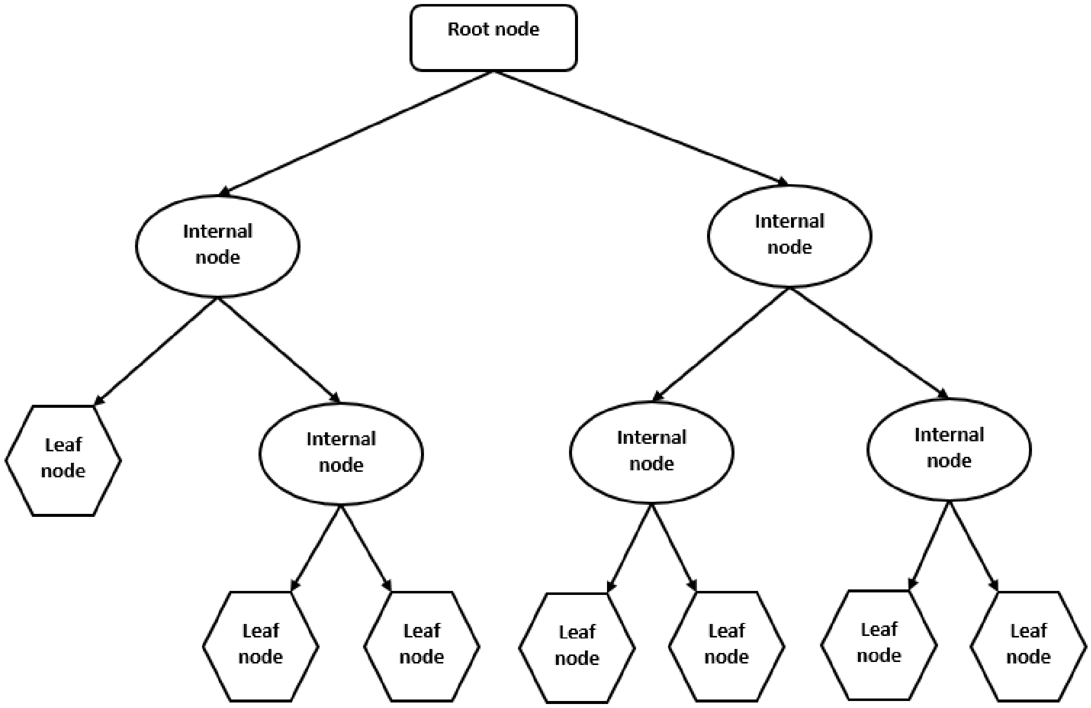


Figure 16. Decision Tree Structure

Random forest decision tree is ensemble-learning method in which decision trees are generated using a random selection of attributes at each node to determine the split (Han et al., 2011). Random forests can be built using bootstrap aggregating (also known as bagging) with random attribute selection. The general procedure to generate k decision trees for the ensemble is as follows. For each iteration, a training set is sampled with replacement from training tuple. To construct a decision tree classifier, decision tree model randomly selects, at each node, the attribute (from the list of attributes) as candidates for the split at the node. The trees are grown to maximum size and are not pruned. In addition, it is important to note that random forests do not overfit (Breiman, 2001).

Classification Method: All 135 data points consisting of sand binder characteristics and disc-shaped specimen test results were collected and classification analysis was performed using

Rapidminer software. In this study, disc-shaped specimen test results represent attributes data and class number assigned to the data represents responses. For validation, 0.6 split ratio and stratified sampling method was considered. This means 60 percent data (10 data points) from each class will be used to train the model and 40 percent data (6 data points) will be used to test the model for accuracy of prediction.

Bagging (Bootstrap aggregating) is model averaging approach proposed by Breiman (1996) which averages a given procedure over many samples, to reduce its variance and avoid overfitting. Bagging is usually applied to decision tree methods to improve the stability and accuracy of machine learning algorithms used in statistical classification. In this classification approach, random forest was used that is composed of decision trees and bagging (parameters: 0.9 sample ratio and 10 iterations) was applied to a decision tree. Decision trees and accuracy matrix are generated as outputs of this analysis.

Results and Discussion

Analysis of test results were conducted using Minitab software. The prime goal of these analysis was to see if these test results are significantly different for each sand system class. To perform analysis of Variance (ANOVA), it is important to confirm that the residuals of these test results are normally distributed and test results have equal variances for all classes. But, these assumptions did not come true for these test results and therefore ANOVA is not appropriate to compare these results. Another way is nonparametric way e.g. Kruskal-Wallis test (generalization of Mann-Whitney test) and Mood's median test (Median test, 2016). Kruskal-Wallis test does not assume normal distribution, but it does assume variance is approximately equal across samples. Hence where assumption does not hold, the Mood's median is the only alternative. Therefore, in this study Mood's median test was performed to test the medians of the populations from which samples are drawn are identical or not. The Mood's median test is very robust against outliers, and fairly robust against differences in the shapes of the distributions. Mood's median test hypothesis is shown below.

H_0 = The population medians are all equal

H_1 = The population medians are not all equal

If the p-value ≤ α (significance level) suggests rejecting the null hypothesis and conclude that not all the group medians are equal. If the p-value ≥ α suggest that there is not enough evidence to reject the null hypothesis that the group medians are all equal. Table *2* shows the resulting p-value for Mood's median tests for each disc-shaped specimen test results.

From Table *2*, P- value for all tests are less than considered significance level (0.05), therefore, it can be concluded that there is enough evidence that medians of at least one class for each of the disc-shaped specimen tests is significantly different. To study in more detail regarding differences between classes, 95% C.I. of each class for each of the tests were considered. Interval plots for median with 95 percent confidence limits for mean for all test results were generated and shown in Figure 17 to Figure 25.

Table 2. P-Values for Mood's Median Test

Disc-shaped specimen test results	p-value
Specimen Weight	0
Permeability	0
Hot Permeability	0
Impact Strength	1.052E-09
Abrasion Loss	0
Retained Strength	1.9E-15
Mass Loss	0
Longitudinal Distortion	0
Radial Distortion	0

After performing non-parametric test such as Mood's median test, in this case, it is appropriate to use interval plots for comparison because all the test results for individual class follow a normal distribution. This was confirmed by performing Ryan-Joiner normality tests (Ukponmwan and Ajibade, 2017) on all the test results individually for each of the nine classes.

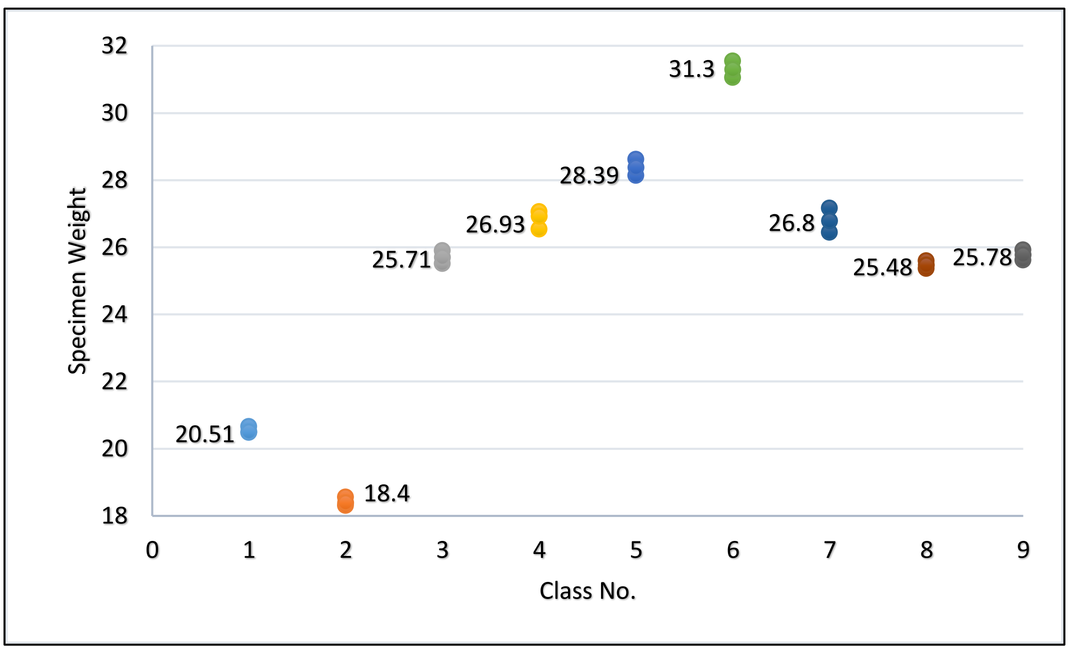


Figure 17. Interval Plot of Specimen Weight

For a disc-shaped specimen test, if 95% C.I. of a class overlaps with at least one other class then it is assumed that a particular class cannot be categorized using a single disc-shaped specimen test. As for example, 95% C.I. of class 4 for specimen weight (Figure 17) overlaps with class 7, therefore class 4 cannot be categorized using a single observation of specimen weight. Conversely, 95% C.I. of class 2 does not overlap with any other class, therefore class 2 can be categorized using a single specimen weight observation.

Specimen weight of class 1 and class 2 are different (Figure 17) because of the shape of sand grains in both classes. Because of the angularity of the sand grains, class 2 specimen weight is lower as it may have more air entrapped than the more rounded sand grains in class 1. As a result, class 2 provides greater venting advantage (i.e. higher permeability- Figure 18 and hot permeability-Figure 19) and lower impact strength (Figure 20) compared to class 1.

In contrast, class 8 and class 9 have no significant difference in specimen weight as both classes have same sand, binder type, binder level. The only difference is the binder supplier. Variation in specimen weight is expected in class 3, 4, 5, 6 and 7 because of either different sand type and/or binder level and binder type. Consequently, no difference between class 8 and 9 can be identified in permeability (Figure 18), hot permeability (Figure 19) and impact strength (Figure 20). However, little difference can be seen in abrasion loss (Figure 21) and TDT results (Figure 23, Figure 24, and Figure 25).

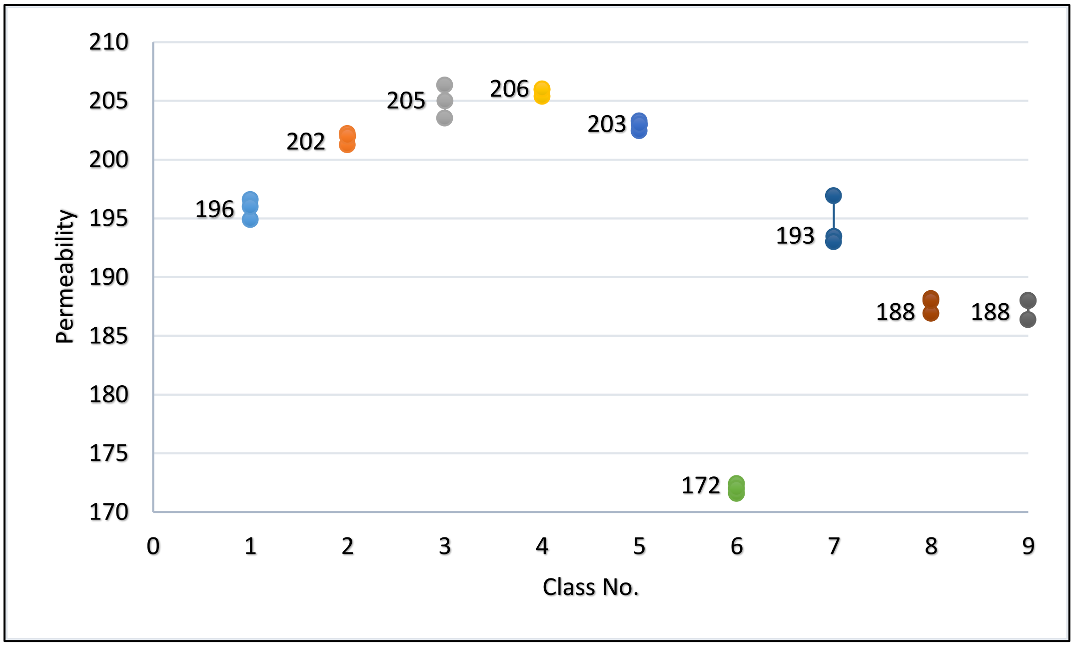


Figure 18. Interval Plot of Permeability

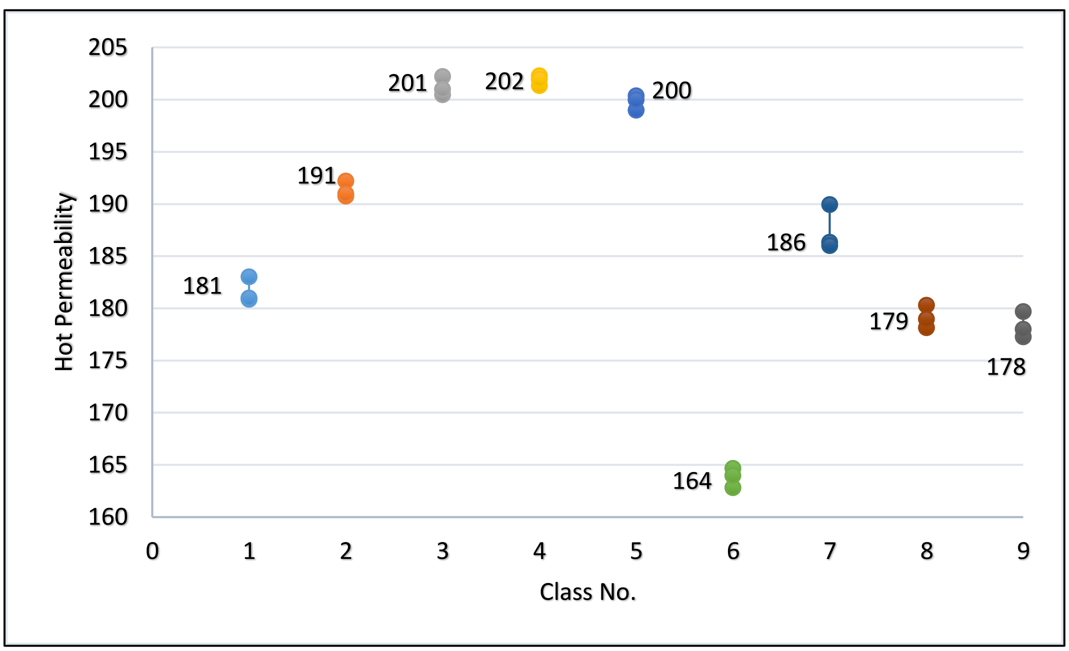


Figure 19. Interval Plot of Hot Permeability

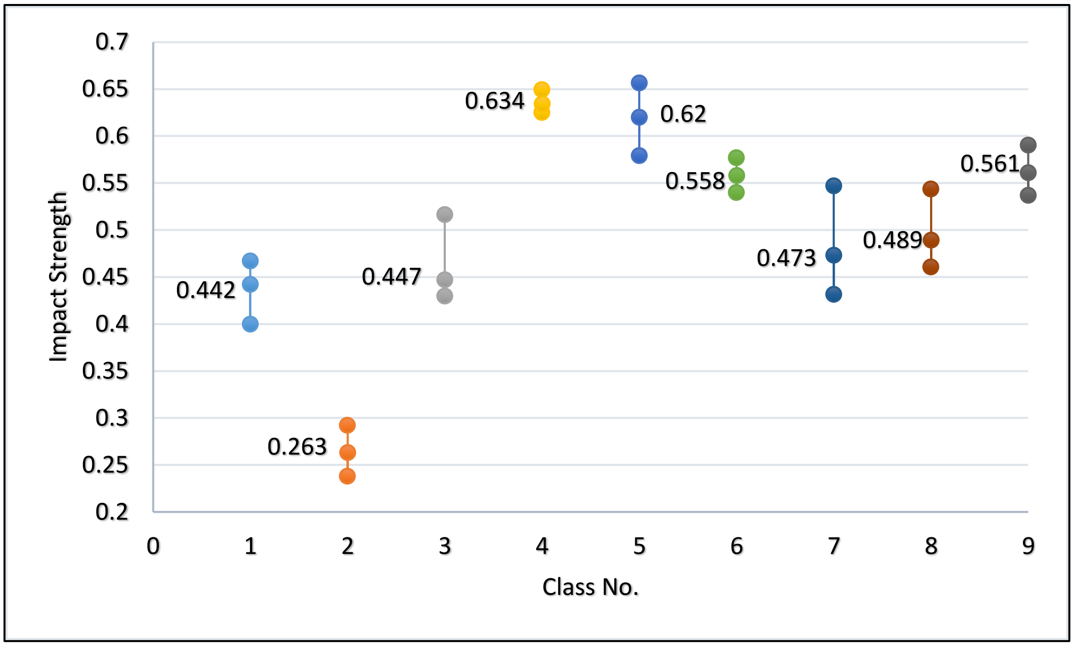


Figure 20. Interval Plot of Impact Strength

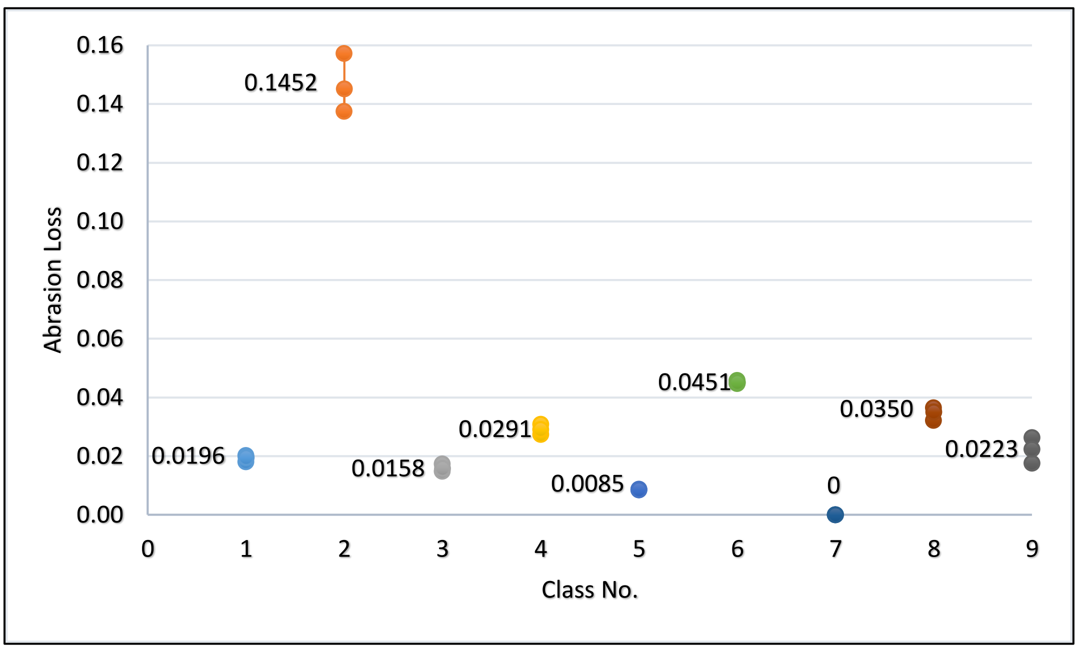


Figure 21. Interval Plot of Abrasion Loss

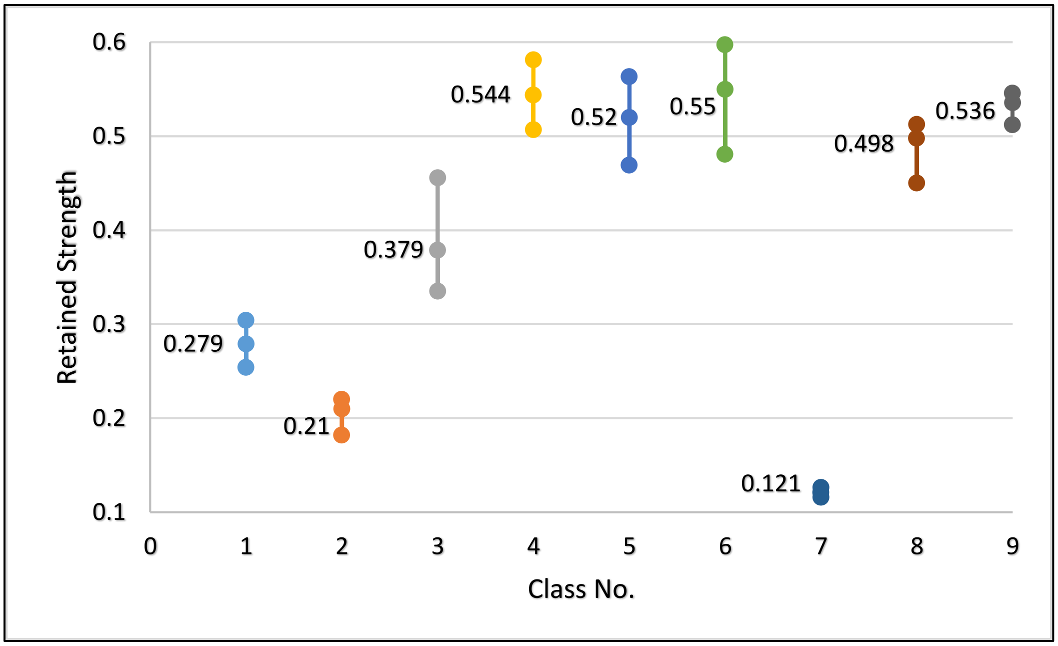


Figure 22. Interval Plot of Retained Strength

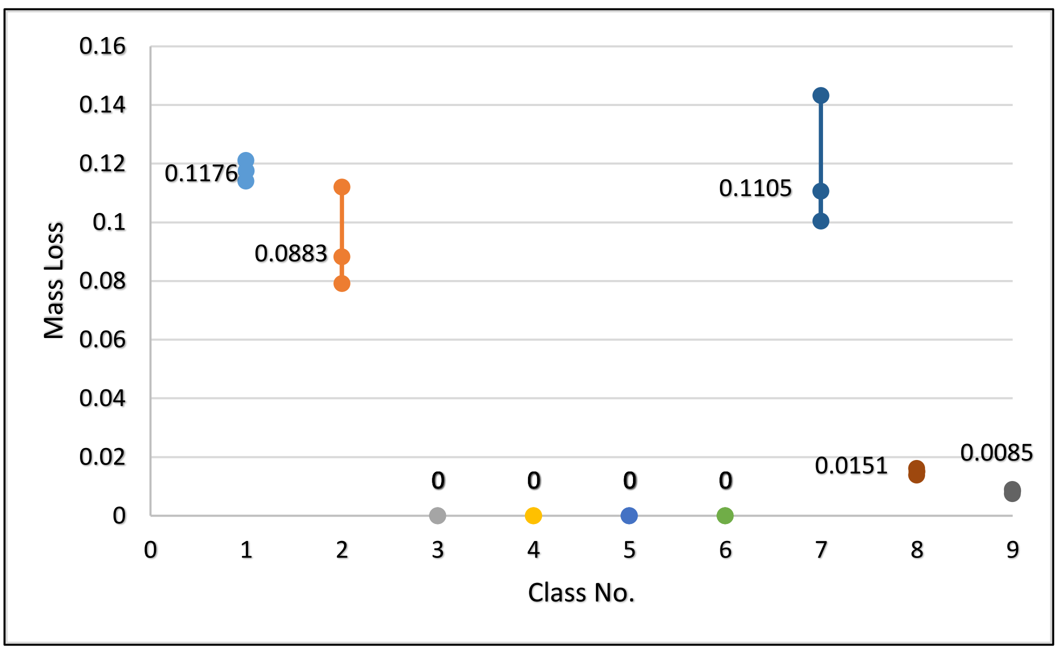


Figure 23. Interval Plot of Mass Loss

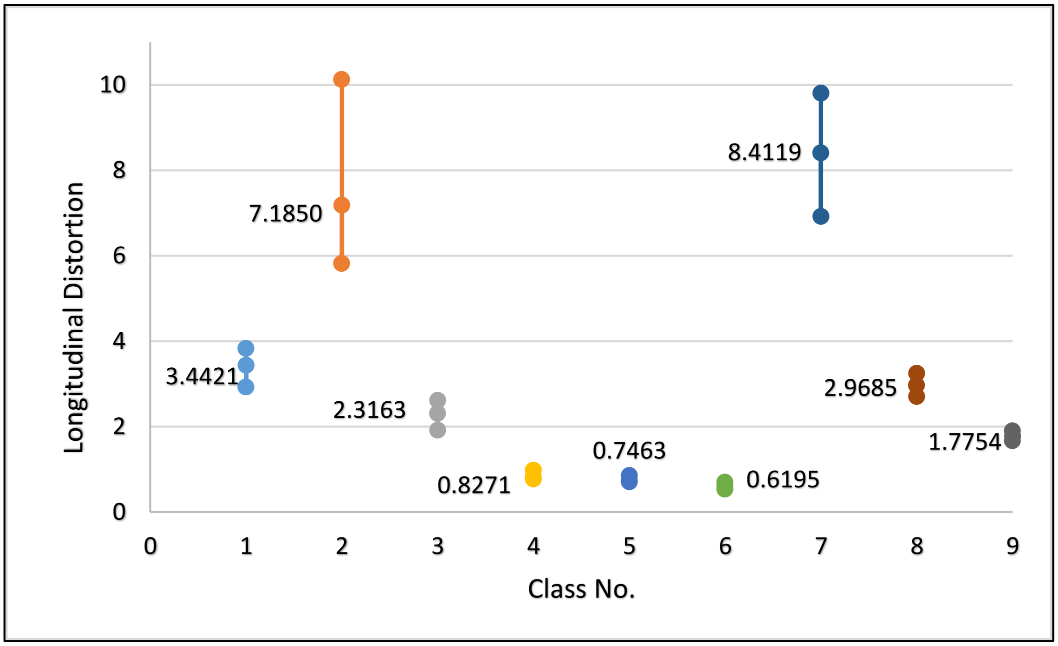


Figure 24. Interval Plot of Longitudinal Distortion

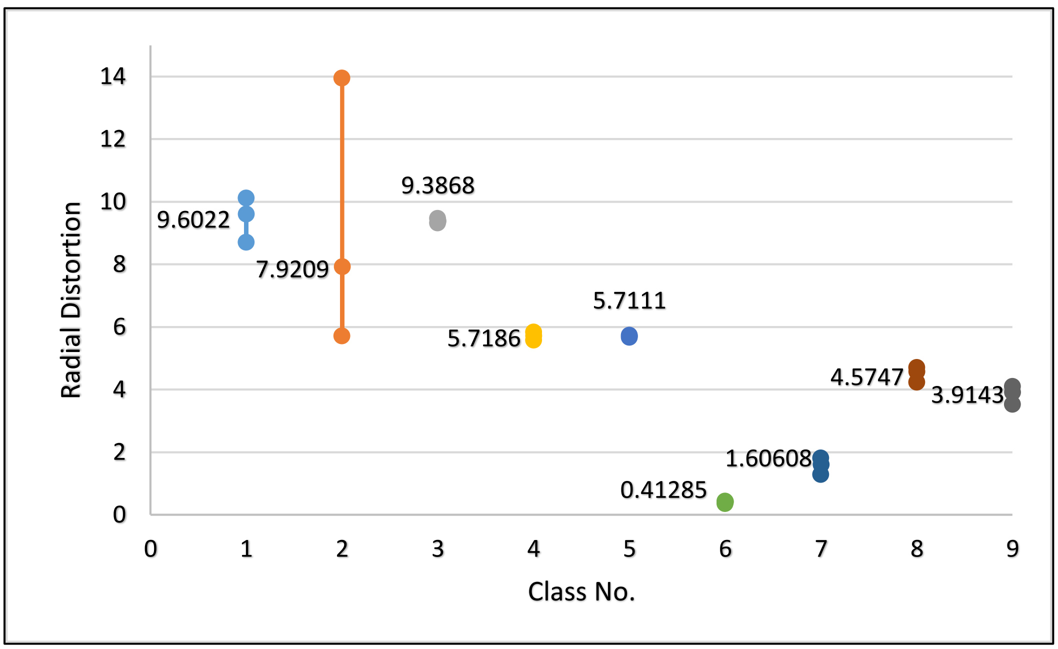


Figure 25. Interval Plot of Radial Distortion

Results of these interval plots in terms of whether these tests can identify a class from rest of the classes based on single observation is summarized in Table 3. From these interval plots, it can be interpreted that there is not a single test result that can be used to classify all the nine sand systems. Multiple test results must be used to classify these sand systems. Therefore, an advanced approach of supervised learning (classification) was considered for further analysis.

Table 3. Summary Results of Interval Plots

	Can a test identify a significantly different class?								
Class No.	Specimen Weight	Permeability	Hot Permeability	Impact Strength	Abrasion Loss	Retained Strength	Mass Loss	Longitudinal Dist.	Radial Dist.
1	Yes	-	-	-	-	Yes	-	-	-
2	Yes	-	-	Yes	Yes	Yes	-	-	-
3	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-
5	-	-	-	-	Yes	-	-	-	-
6	Yes	Yes	Yes	-	Yes	-	-	-	Yes
7	-	-	-	-	Yes	Yes	-	-	Yes
8	-	-	-	-	-	-	-	-	-
9	-	-	-	-	-	-	-	-	-

As a result of classification analysis, the software generated an accuracy matrix as shown in Table *4*. The matrix shows accuracy of the predicting model is 100 % that means that all the classes were predicted accurately based on the selected attributes and classification method. Class recall and precision is 100 %. Recall is the ratio of the number of relevant records retrieved to the total number of relevant records in the database. While precision is the ratio of the number of relevant records retrieved to the total number of irrelevant and relevant records retrieved.

Table 4. Accuracy Matrix of the Model

Accuracy: 100%	True 1	True 2	True 3	True 4	True 5	True 6	True 7	True 8	True 9	Class Precision
Pred. 1	6	0	0	0	0	0	0	0	0	100%
Pred. 2	0	6	0	0	0	0	0	0	0	100%
Pred. 3	0	0	6	0	0	0	0	0	0	100%
Pred. 4	0	0	0	6	0	0	0	0	0	100%
Pred. 5	0	0	0	0	6	0	0	0	0	100%
Pred. 6	0	0	0	0	0	6	0	0	0	100%
Pred. 7	0	0	0	0	0	0	6	0	0	100%
Pred. 8	0	0	0	0	0	0	0	6	0	100%
Pred. 9	0	0	0	0	0	0	0	0	6	100%
Class Recall	100%	100%	100%	100%	100%	100%	100%	100%	100%	

It is required to observe decision trees to understand how the decision regarding classes have been made. By observing decision tree, it can be interpreted that which tests differentiate between selected sand systems. Figure 26, Figure 27 and Figure 28 show some of the decision trees that differentiate between all 9 sand systems.

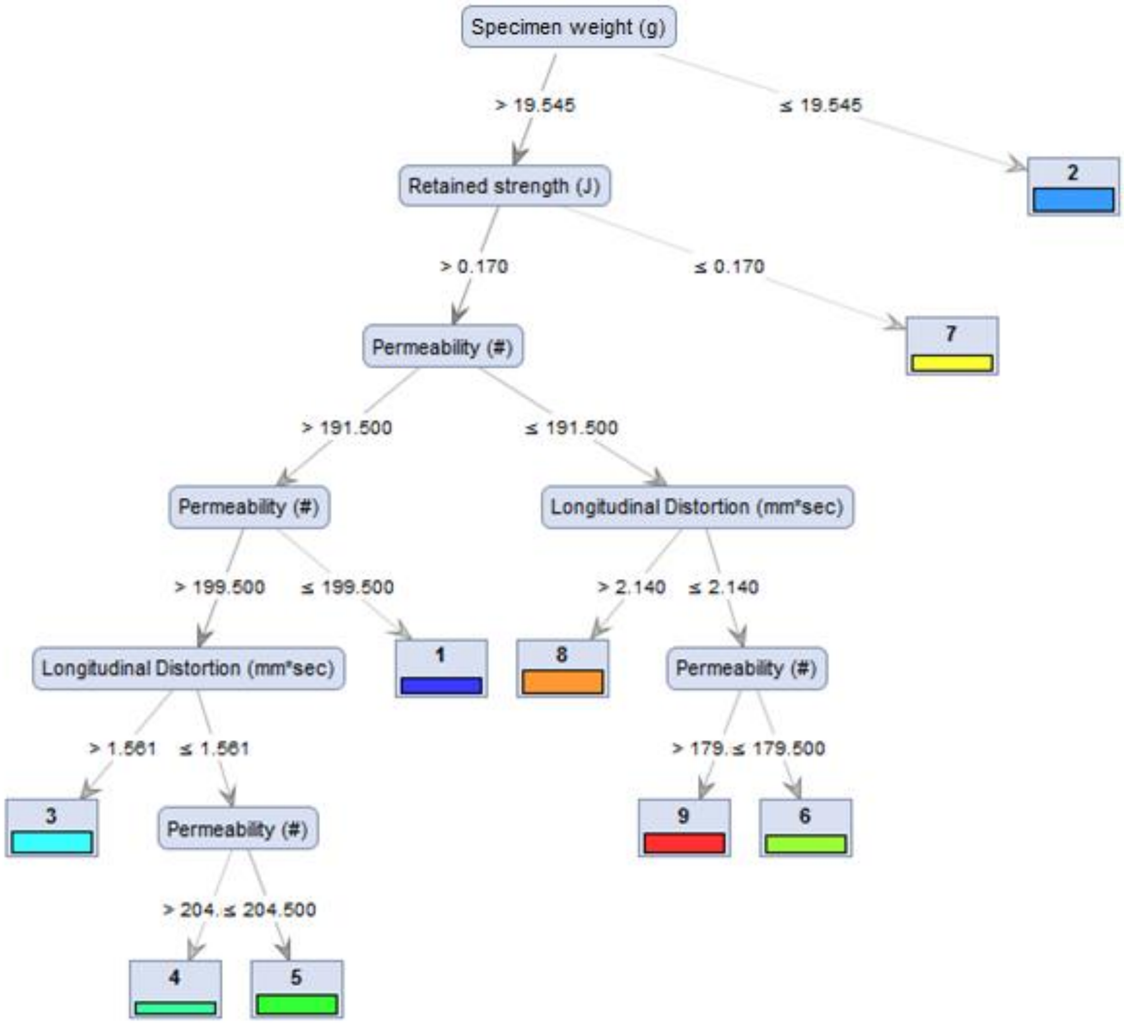


Figure 26. Decision Tree 1

Decision tree 1 (Figure 26) shows that specimen weight, permeability, longitudinal distortion, and retained strength together can classify selected nine classes of sand systems. Specimen weight can differentiate between class 1 and 2. The main difference in sand binder characteristic between class 1 and 2 is sand in class 2 is more angular and has 3 screen distribution compared to 2 screen distribution of class 1 sand. TDT (Longitudinal distortion) differentiates between unintended changes such as change in a binder chemistry (class 8 and 9) and change in binder level (class 3 and 5). Permeability test and retained strength (impact strength after TDT) differentiate between fundamental changes in a sand system such as change in process type, binder type, and sand type.

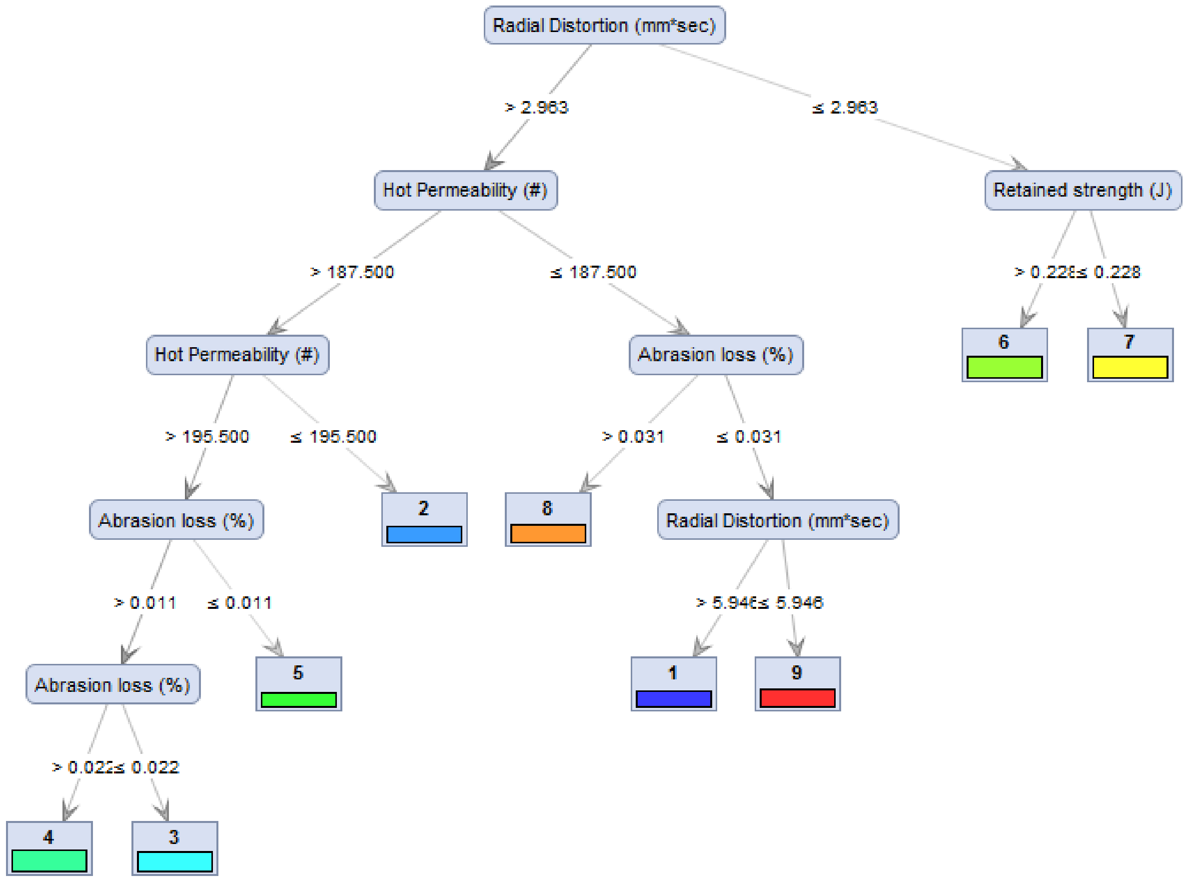


Figure 27. Decision Tree 2

Similar interpretation can be done from decision tree 2 and 3 (Figure 27 and Figure 28). From Figure 27, it can be interpreted that radial distortion, retained strength, hot permeability, and abrasion loss together can classify selected classes of sand systems. Also, hot permeability can differentiate between class 1 and 2. Abrasion test can differentiate between class 8 and 9. From Figure 28 it can be interpreted that permeability, hot permeability, specimen weight, abrasion loss, and mass loss together can classify these 9 classes. TDT mass loss can differentiate between class

8 and 9 that represent unintended change in a sand system. In addition, abrasion test and hot permeability test differentiate between fundamental changes in a sand system.

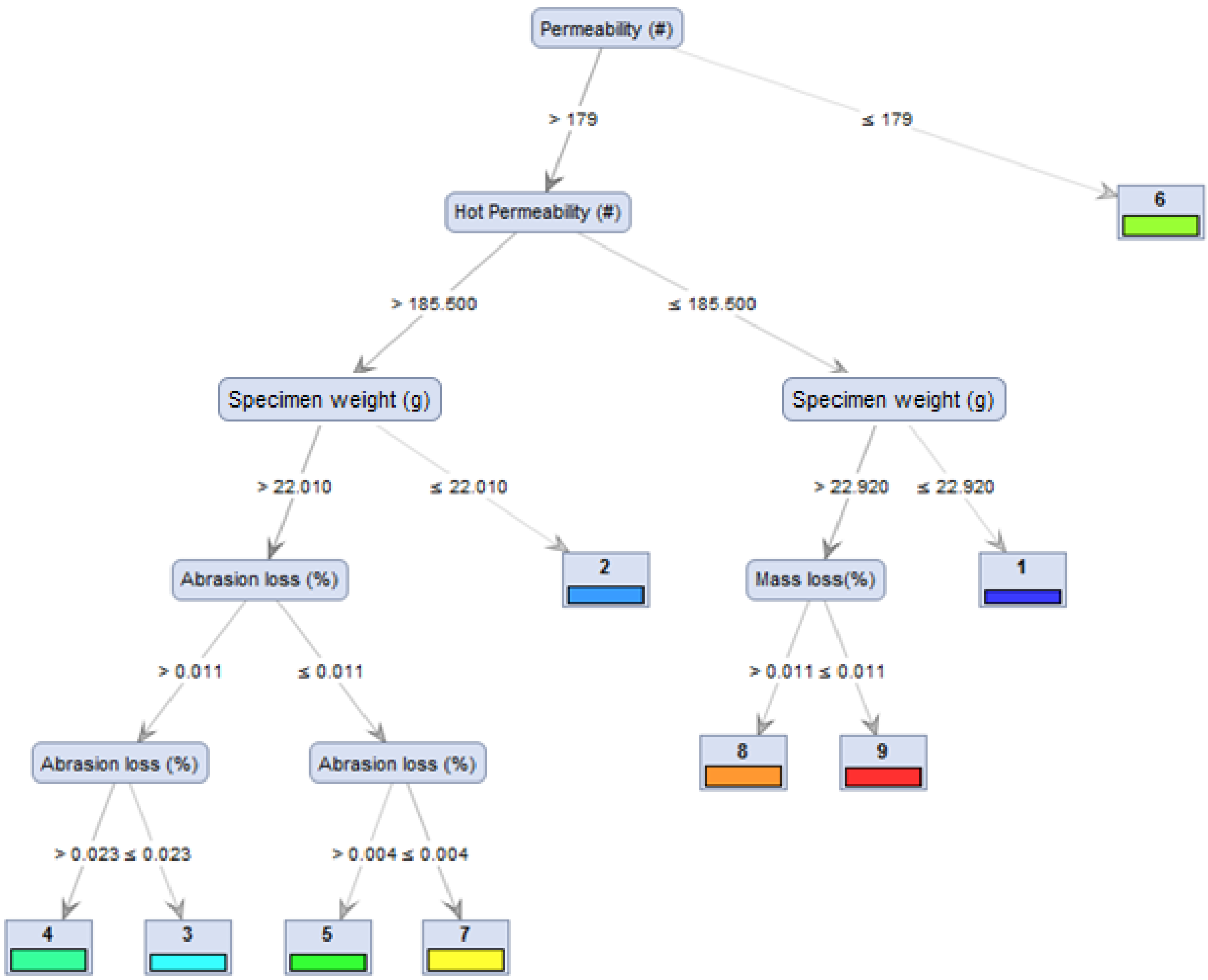


Figure 28. Decision Tree 3

Conclusion

In this study, disc-shaped specimen tests were used to classify changes in different sand systems using decision tree method. It can be concluded that these disc-shaped specimen tests can categorize between the nine sand systems that have differences which may affect casting quality. This study shows that the classification approach might be useful in categorizing changes in a sand system in a foundry if disc-shaped specimen test data are supplied as an input.

Further, a SPC method can be developed using different types of control charts such as Individual chart, X-bar chart, R chart, EWMA chart etc. that uses the disc-shaped specimen test results. These types of charts may help to identify a shift in a mold/core making process which may occur due to a change in raw material (sand, binder, additives etc.) and/or process parameters. This study supports to develop a SPC method to detect a shift in mold/core making process. Once SPC method is established, quality control framework can be implemented. This framework suggests that when a shift in a sand system is detected then a casting trial needs to be performed to realize the effect of the change on casting quality.

CHAPTER III

STATISTICAL PROCESS CONTROL

The objective of this phase is to develop a SPC method that can be used to quickly detect changes in chemically bonded sand systems. For this, key feature(s) of the disc-shaped specimen tests needs to be identified and an appropriate technique needs to be implemented for detection of a process shift. A pilot study was conducted to identify features of the disc-shaped specimen test results that can be used to quickly identify a change in sand system.

Pilot Study

In previous chapter, several changes such as sand grain shape (class 1 and 2); change in binder level (class 3 and 5) and change in binder chemistry (class 8 and 9) were studied. Classification results shows that these types of changes can be identified by these disc-shaped specimen test results. However, performing a greater number of tests to administer the process can cost more money as it requires more equipment, time, and effort. Therefore, it would be great if only one test can detect a change in sand system. To study, which test can detect a shift in sand system, some other changes in a sand system, in a preliminary SPC study, such as change in sand screen distribution (3D printed sand system) and an internal change in binder level (PUCB sand system) was considered. The sand system characteristics are shown in Table 5.

Class 1 and class 8 sand systems are the same as in classification study. While class 10 and 11 were added in this research to study the unintended changes. There some differences present in class 1 and 11 as well as class 8 and 10 that can be well thought-out as subtle changes.

Alteration between class 1 and 11 is that the sand screen distribution in class 11 is higher than in class 1. Class 8 and 10 have same PUCB binder. PUCB binder has two different binders called part 1 and part 2 binders. The respective proportions of class 8 binder (part 1/part 2) were flipped in class 10.

Table 5. Sand System Characteristics – SPC Study

Class No.	Process type	Sand type	Sand shape	Binder type	Sand size (AFS-GFN)	Sand screen distribution	Binder level (%)
1	3D	Silica	Sub-angular	Furan	80	2	1.2
8	Cold-box	Silica	Sub-angular	PUCB 1	60	3	0.6 (Part 1/Part2:55%/ 45%)
10	Cold-box	Silica	Sub-angular	PUCB 1	60	3	0.6 (Part 1/Part2:45%/ 55%)
11	3D	Silica	Sub-angular	Furan	80	4	1.2

In previous study, we considered change in grain shape (sub-angular – class 1 vs angular – class 2) and observed that it can be distinguished by specimen weight. In this research study, class 1 and class 11 are considered for comparison and class 8 and class 10 are considered for comparison. Similar to previous study, 15 data points were measured for these additional sand systems. Disc-shaped specimen tests were performed using the same testing parameters and the results of these tests were recorded. The average and standard deviation of the results are presented in Table 6.

Table 6. Disc-Shaped Specimen Test Results

Class No.	1	1	11	11	8	8	10	10
	Avg.	S.D.	Avg.	S.D.	Avg.	S.D.	Avg.	S.D.
Permeability	195.7	1.53	198.8	1.37	187.5	1.12	187.6	1.54
Hot Permeability	181.9	1.94	185.4	2.29	179.2	1.93	179.6	2.74
Specimen weight	20.57	0.16	20.27	0.14	25.48	0.2	25.39	0.23
Impact strength	0.433	0.06	0.386	0.039	0.502	0.074	0.471	0.07
Abrasion loss	0.0191	0.001	0.0221	0.004	0.0342	0.003	0.0384	0.006
Retained strength	0.279	0.045	0.278	0.028	0.481	0.056	0.475	0.067
Mass loss	0.117	0.006	0.115	0.006	0.015	0.002	0.014	0.004
Longitudinal Distortion	3.375	0.818	3.817	0.521	2.974	0.495	3.122	0.333
Radial Distortion	9.41	1.274	7.814	1.525	4.465	0.42	4.176	0.263

Two sample t-tests were performed for each of these test results to compare class 1 with class 11 and class 8 with class 10. P-values of these comparisons is shown in Table 7. Results of t-tests suggests that these disc-shaped specimen tests are able to distinguish between the targeted changes in the sand systems.

Table 7. P-Values of Two Sample t-Tests

Comparison between classes	1 vs 11	1 vs 11	8 vs 10	8 vs 10
	P-value	95% C. I.	P-value	95% C. I.
Permeability	0.000	(-4.157, -1.976)	0.894	(-1.085, 0.952)
Hot Permeability	0.000	(-5.127, -1.940)	0.649	(-2.186, 1.386)
Specimen weight	0.000	(0.1837, 0.4110)	0.261	(-0.0723, 0.2563)
Impact strength	0.019	(0.0083, 0.0857)	0.264	(-0.0242, 0.0849)
Abrasion loss	0.030	(-0.00563, -0.00032)	0.046	(-0.00826, -0.00007)
Retained strength	0.947	(-0.0277, 0.0295)	0.783	(-0.0404, 0.0530)
Mass loss	0.331	(-0.00259, 0.00742)	0.697	(-0.00208, 0.00305)
Longitudinal Distortion	0.091	(-0.960, 0.076)	0.347	(-0.466, 0.170)
Radial Distortion	0.004	(0.543, 2.650)	0.034	(0.024, 0.555)

It should be noted that radial distortion and abrasion loss are showing significant differences between these systems. Results of previous chapter also suggest that TDT and abrasion test are important in classifying different sand systems. TDT mimic the behavior of sand system under presumed parameters such as temperature and pressure. In addition, TDT creates multidimensional test results such as longitudinal distortion, radial distortion and backside temperature for up to 90 seconds. To study the viability of profile monitoring, another pilot work is conducted that uses TDCs (longitudinal and radial distortion curves). To investigate TDCs profile monitoring, class 1 vs class 11 and class 8 vs class 10 were considered. Average curves for longitudinal and radial TDCs for class 1 and class 11 are shown in Figure 29 and Figure 30 respectively. Similarly, average longitudinal and radial TDCs for class 8 and class 10 are shown in Figure 31 and Figure 32 respectively.

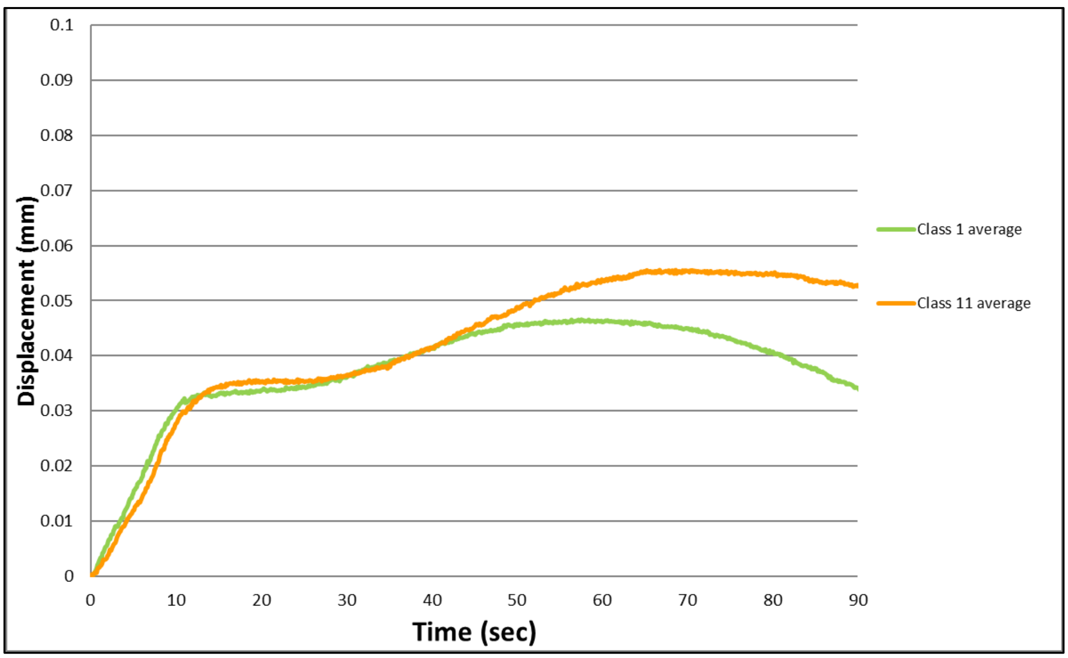


Figure 29. Average Longitudinal TDC – Class 1 and 11

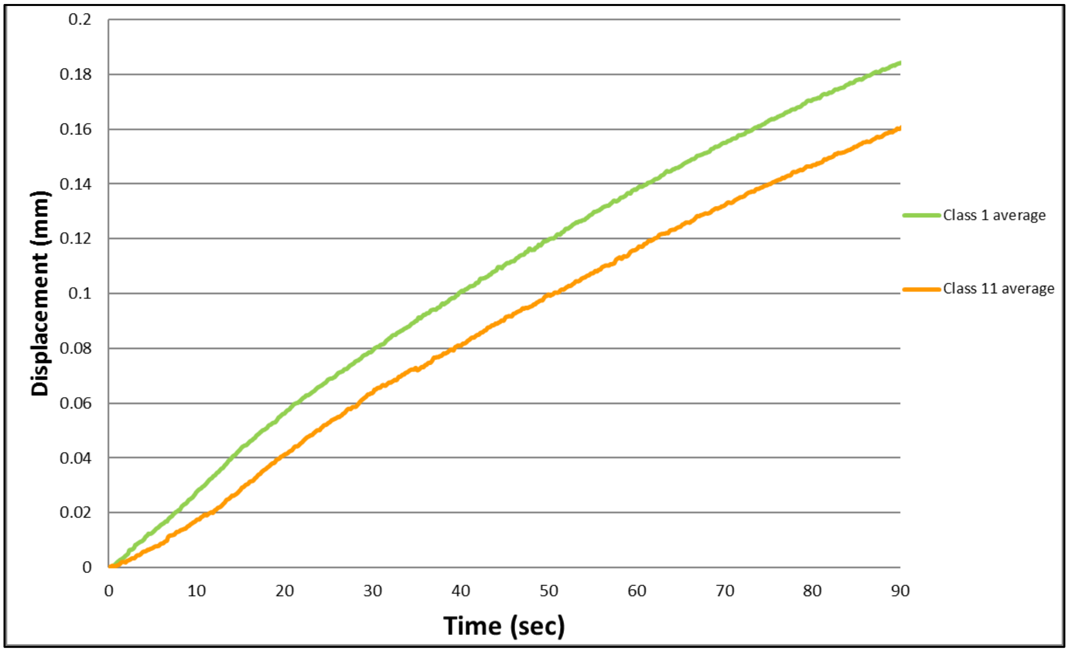


Figure 30. Average Radial TDC – Class 1 and 11

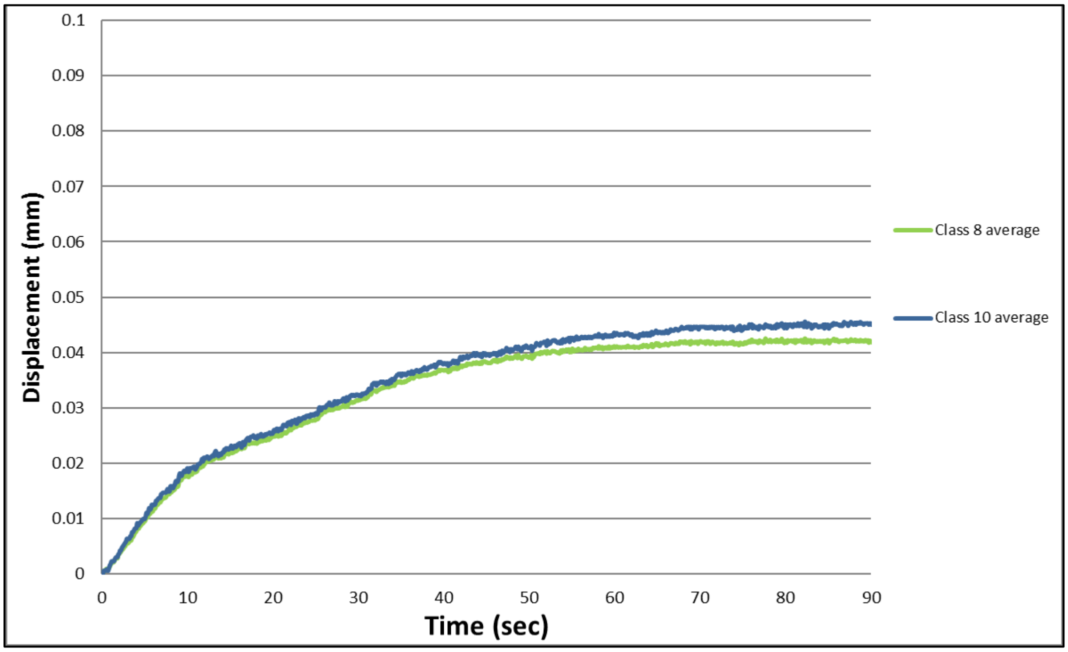


Figure 31. Average Longitudinal TDC – Class 8 and 10

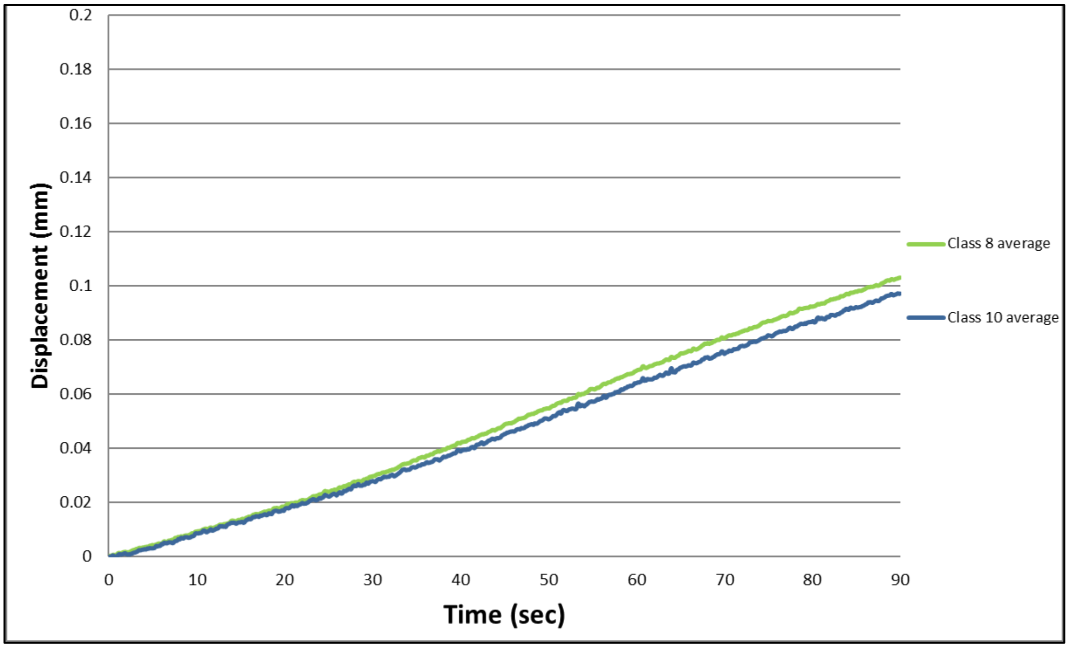


Figure 32. Average Radial TDC – Class 8 and 10

For this analysis, Longitudinal TDC is broken down into several curve segments: initial curve, middle curve, end curve etc. (Figure 33). Number of segments depends on number of mountains and valleys in the curves. While radial TDC was not divided in segments because these curves are almost linear.

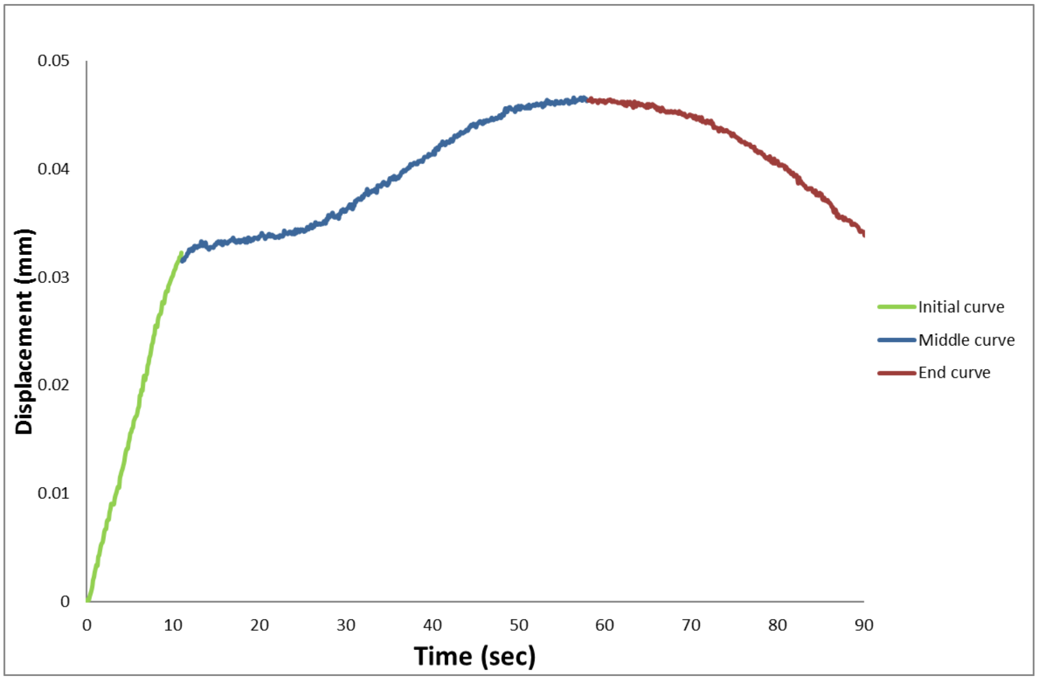


Figure 33. Segments of Longitudinal Curve

A linear regression line so called predicted line can be fitted from the collected TDT data to predict the displacement value for a given time as shown in Figure 34. Intercept with Y-axis and slope of this predicted lines are used to identify any change in the sand system. Intercept and slope are calculated using the statistical function provided in the Excel spreadsheet. Control charts of these characteristics can help detect any deviation from the normal behavior.

Individual control charts for intercept and slope of predicted lines for different curve segments were developed for all sand system. For control chart, control limits (mean ± 3*standard deviation) and average is calculated based on TDT data of ten disc-shaped specimens of class 1 (for comparing it with class 11) and class 8 (for comparing it with class 10). TDT data of all disc-shaped specimens of class 1 and 11 and class 8 and 10 were plotted in the same chart. Figure 35 to Figure 40 show control charts for intercept and slope of the predicted lines (initial line, middle line and end line). Figure 41 and Figure 42 show individual control charts for intercept and slope of radial TDC.

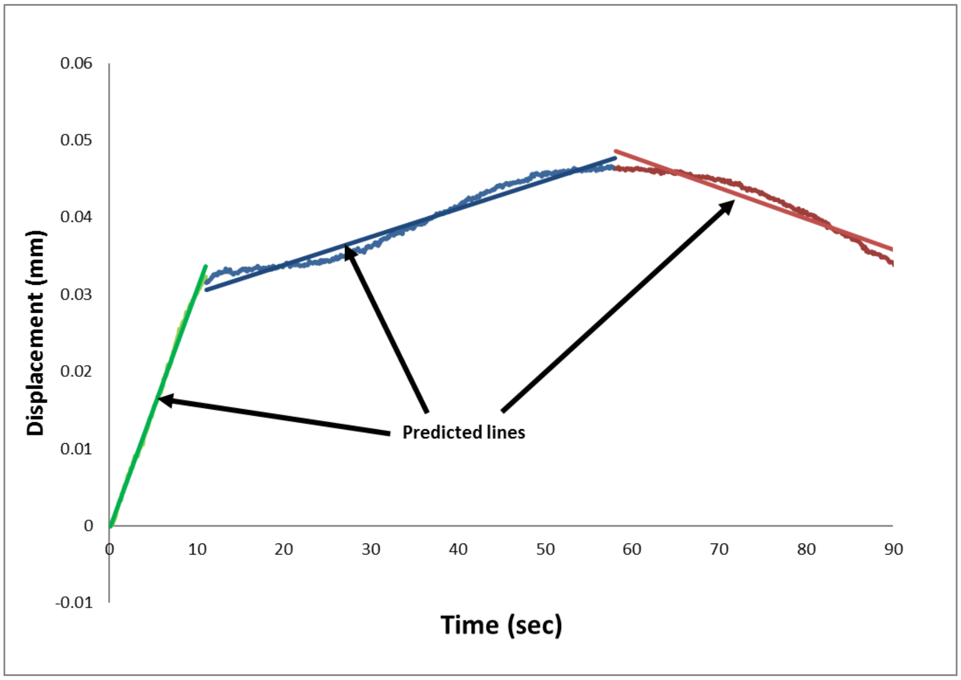


Figure 34. Predicted Line Segments of Longitudinal Curve

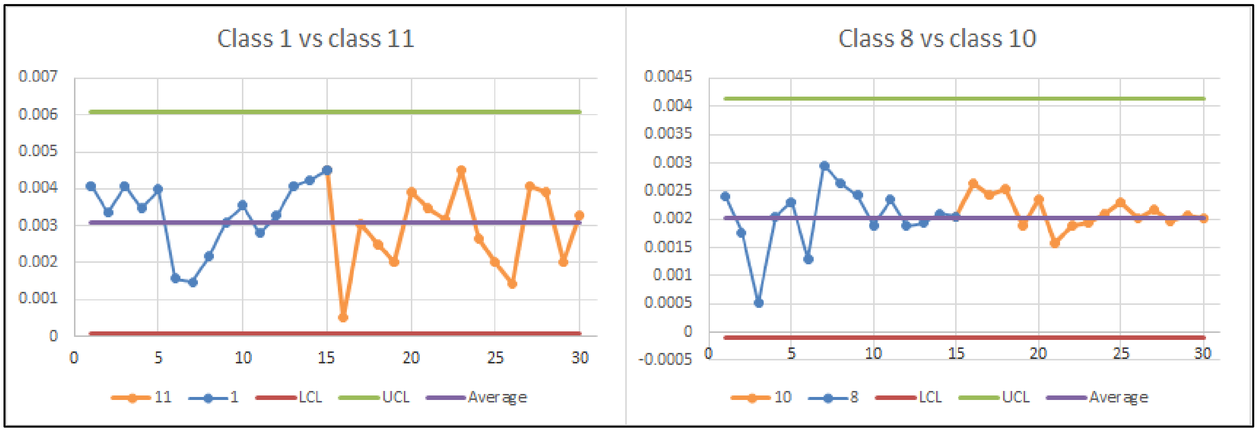


Figure 35. Individual Control Chart for Initial Line Slope

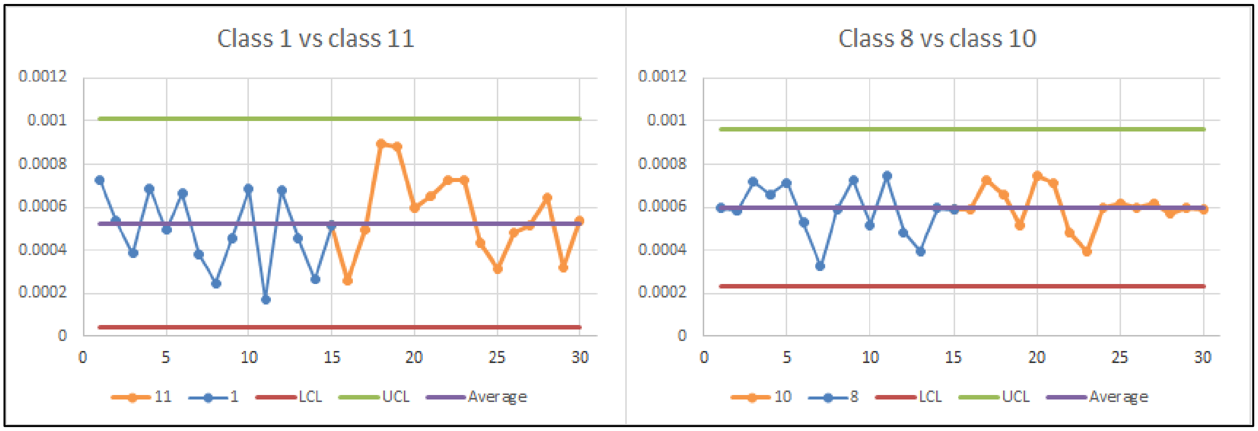


Figure 36. Individual Control Chart for Middle Line Slope

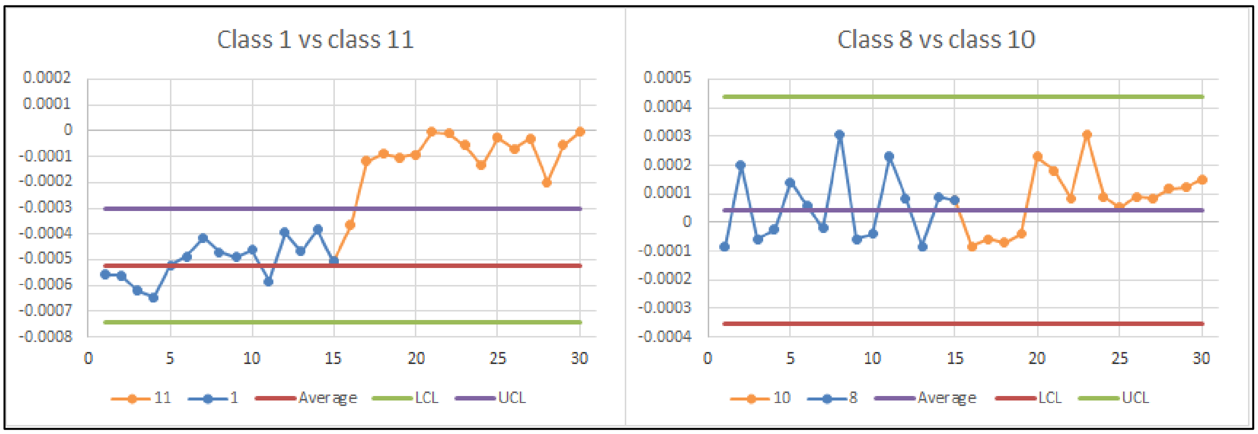


Figure 37. Individual Control Chart for End Line Slope

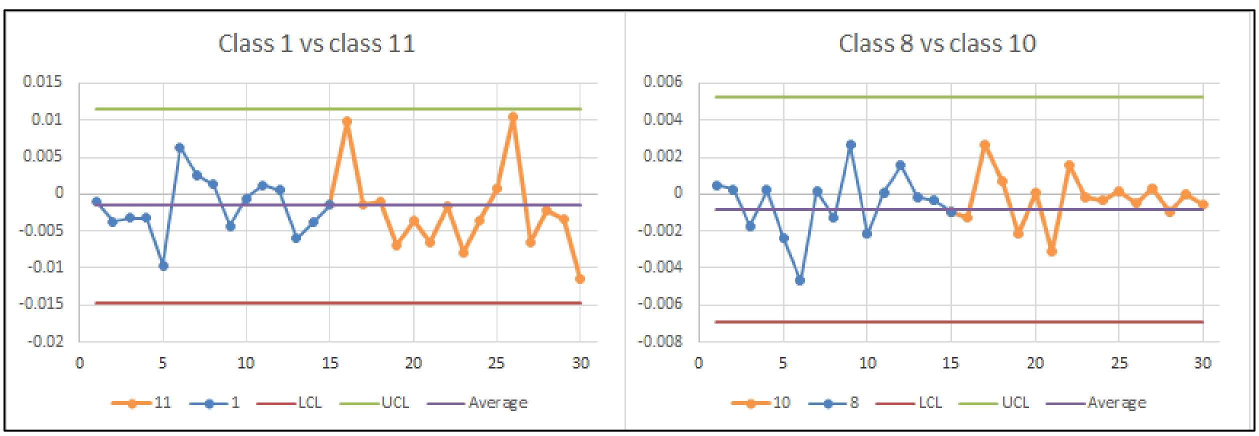


Figure 38. Individual Control Chart for Initial Line Intercept

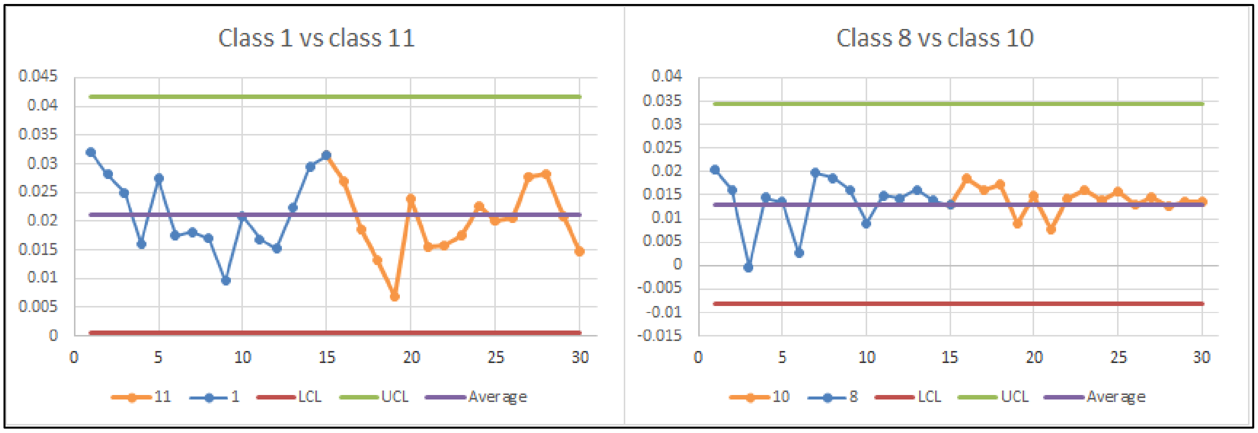


Figure 39. Individual Control Chart for Middle Line Intercept

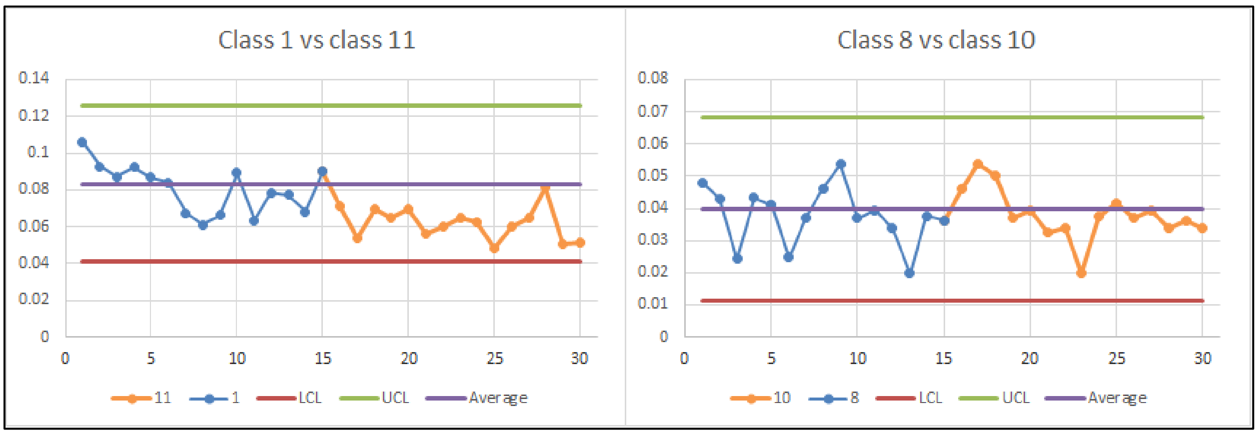


Figure 40. Individual Control Chart for End Line Intercept

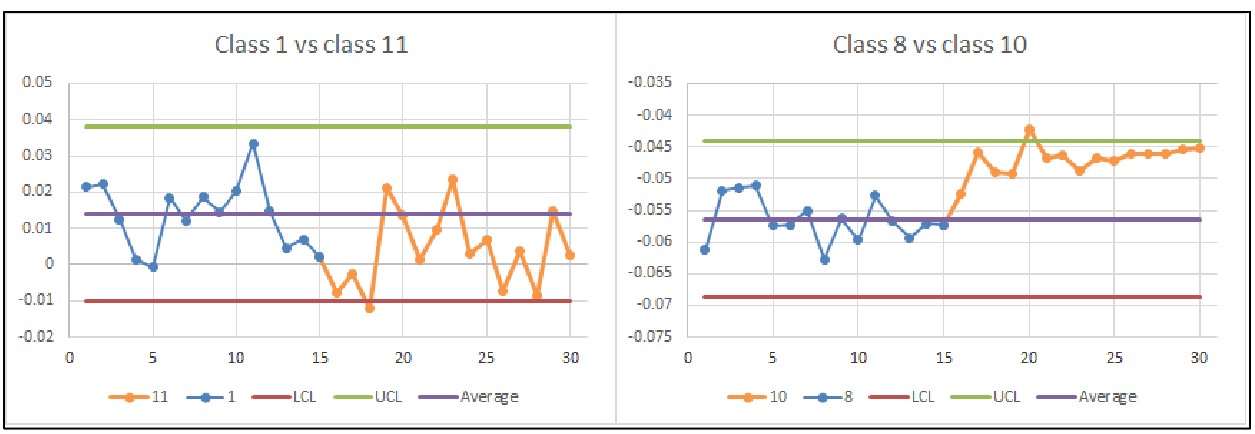


Figure 41. Individual Control Chart for Radial Intercept

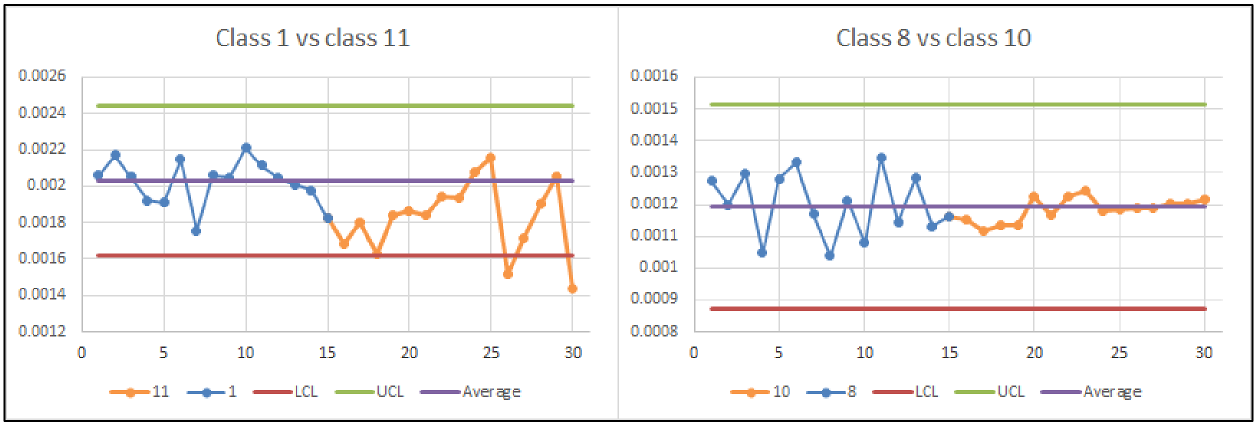


Figure 42. Individual Control Chart for Radial Slope

Control charts for initial line and middle line do not depict any process change. However, control chart for end line slope (Figure 37) clearly signals out of control state for class 11(Class 1 vs class 11), while eleven consecutive points (20 to 30) are above average line for class 10 (Class 8 vs class 10). Figure 40, control chart for end line intercept, shows twelve consecutive points (16 to 27) are below the average line for class 11. In addition, intercept and slope of radial TDC signal out of control state for class 11 (Figure 41 and Figure 42). Slope of radial TDC for class 10 has 9 consecutive points below the average.

Class 8 and class 10 average TDCs are almost alike (Figure 31 and Figure 32). For class 8 vs class 10, as none of these individual control charts showed clear indication of an “out of control” state as soon as the shift occurred, EWMA control chart was used to detect a small shift like this. EWMA control chart for radial intercept is shown in Figure 43. For this chart, weight factor (λ) was considered as 0.25. Typically, EWMA control chart is used for sustained shift in a process, while the shift considered in the study is more of a temporary in nature which may occur for small period and may disappear quickly before foundry engineer can observe it. Therefore, using EWMA is not appropriate in detecting the several of these shifts.

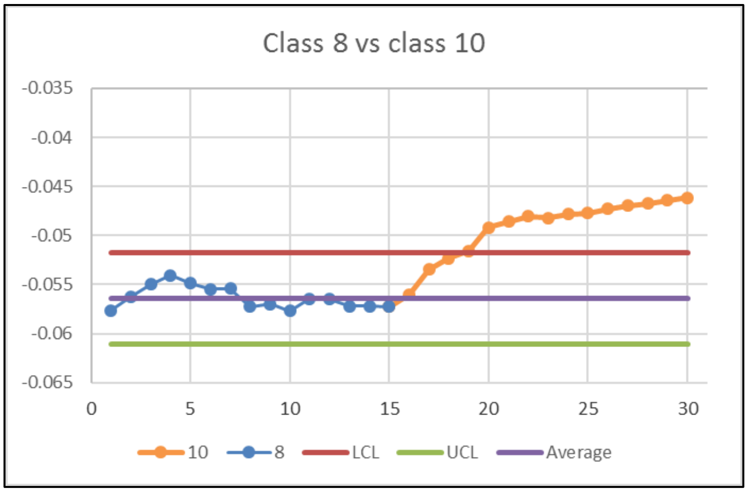


Figure 43. EWMA Control Chart for Radial Intercept

Results of control charts in terms of ability to detect a shift using above mentioned TDC attributes are shown in Table 8.

Table 8. Control Chart Results

Attributes	Detect shift 1 vs 11	Detect shift 8 vs 10
Initial curve slope	-	-
Middle curve slope	-	-
End curve slope	Yes	Yes
Radial curve slope	Yes	-
Initial curve intercept	-	-
Middle curve intercept	-	-
End curve intercept	Yes	-
Radial curve intercept	Yes	Yes

As results of this initial study shows that attributes of TDCs can be extremely useful in detecting shift in a sand system. Following study is focused on developing a method that uses TDCs to monitor chemically bonded sand systems.

Statistical Process Control using Thermal Distortion Curves

The Goal of this study is to develop a method that a foundry can use for SPC. For foundries, implementing efficient SPC is essential to meeting the ever-increasing demands for high quality and dimensionally reproducible mold/cores. The development of an efficient SPC system is a multi-phase process that is often overlooked in industry. Incorporating new analytical tools, such as Principal Component Analysis (PCA), will not increase SPC system performance if other aspects of the SPC system development process have been ignored. Following are a few examples of key SPC system development aspects.

1. The capability of the measurement systems being used to assess quality must be quantified. If the measurement system exhibits an excessive amount of variability (compared to the process it is attempting to measure) then the system will be incapable (useless) to detect process shifts and/or quality losses.
2. In order to develop appropriate control limits the In-Control behavior of the system must be well understood. This process understanding requires the collection of historically stable process data and the ability to identify and remove assignable causes from the historical data.
3. If an out-of-control signal is detected during real-time monitoring, there needs to be a diagnostic procedure in-place to bring the system back in-control.

Previous research has shown that measurements from disc-shaped specimen tests are better able to discriminate between sand-binder systems compared to traditional test measurements (Patel et al, 2018). The tests that were considered in this recent research were: impact strength, hot permeability, abrasion, thermal distortion test (TDT), and retained strength. The results suggest that measurement taken from these tests may provide the means to effectively monitor incoming sand-binder systems. However, there are numerous tests which can be used to monitor chemically bonded sands, unfortunately, it becomes expensive to rely on multiple tests for process monitoring, especially when the ultimate goal is 100% inspection (i.e., every mold/core produced results in one set of tests) as it requires more specimens, more equipment, and more time.

This study investigates the capability of monitoring sand-binder systems using TDT data. TDT is considered for this purpose because it provides coupled thermal-mechanical sand-binder system behavior at head pressures and temperatures that can be adjusted to represent actual casting scenarios. TDT produces a high-dimensional dataset, as it produces multiple time-series profiles, referred to as TDCs. In order to effectively use this dataset, this study will incorporate multivariate statistical analysis for process monitoring. A multivariate statistical methods performance degrades as the number of variables increase. Due to these reasons, the objective of this research is to investigate the capability of monitoring sand systems exclusively using TDCs from the TDT. In order to effectively use this dataset, this paper will incorporate PCA. More specifically, PCA will be applied to the dataset for the purpose of dimension reduction and monitoring. The proposed monitoring scheme will be demonstrated through a case-study. For this study, six resin coated sand (RCS) binder systems with the same sand and binder type but varying binder levels are analyzed. The ability of the proposed monitoring scheme to detect the shift from one sand-binder system to another will be determined.

Considering the aspects of SPC with respect to this study, it should be noted that the TDT has been shown in previous research to be a measurement system that is highly capable. Furthermore, the historical data collected for this study was obtained from one single batch of Shell RCS and the disc-shaped specimens were prepared and tested in a laboratory environment, which eliminates most of the opportunities for assignable causes. Finally, the purpose of this study is to demonstrate the ability to detect process shifts using the TDT; the development of diagnostic procedures will be the focus of future work.

These six sand systems were supplied by an anonymous industrial partner. Targeted binder levels for these systems are given in Table 1. As a check, loss on ignition (LOI) and grain fineness number (GFN) tests were performed on these six sand systems. Results of LOI and GFN are documented in Table 9 and Table 10, respectively. These six sand systems show quantifiable differences (required to conduct this study) in LOI, however, LOI may not always relate to binder level for certain sand systems such as inorganic sand systems or sand systems in which sand gain weight after performing LOI such as Chromite sand.

Table 9. Target Binder Level and LOI of Sand Systems

System	% binder target	% LOI
1	1.25	1.50
2	2.00	2.30
3	2.75	3.15
4	3.50	3.80
5	4.25	4.40
6	5.00	5.40

For each sand system, fifteen disc-shaped specimens were prepared using the curing parameters, 250 ºC (482 ºF) for 50 seconds. These cure parameters were personally recommended by the AFS 4F committee. After determining LOI and GFN, the following two steps were conducted in this study.

1. Perform TDT and record resulting data matrix
2. Detecting shift in test results using PCA and a Hotelling T^2 chart

Table 10. Percentage Sand Retained in GFN for Sand Systems

Sieve \ System	1	2	3	4	5	6
6	0	0	0	0	0	0
12	0	0	0	0	0	0
20	0	0	0	0	0	0
30	0	0	0	0	0	0
40	0.31	1.59	0.31	0.32	0.41	0.31
50	19.69	19.35	17.40	15.97	17.97	19.69
70	35.70	37.02	37.11	35.85	38.50	35.70
100	29.27	27.80	29.72	30.20	28.95	29.27
140	12.64	11.83	12.89	14.60	11.91	12.64
200	2.07	2.15	2.10	2.64	2.00	2.07
270	0.31	0.26	0.47	0.42	0.26	0.31
PAN	0	0	0	0	0	0

TDT and Resulting Data Matrix

TDT was performed on fifteen disc-shaped specimens for each of the six sand systems and time-series data for longitudinal displacement (LD) and radial displacement (RD) were recorded. TDT temperature was set at 1000 ºC (1832 ºF) and head pressure was set at 4.5N which is equivalent to 9” head height for a cast iron casting (15” head height for Aluminum casting). These test parameters were also recommended by the AFS 4F committee which are suitable for medium size cast-iron casting. To minimize experimental error, the order of the samples was randomized during specimen production and testing. It is important to mention that TDT parameters are suited for medium size cast iron castings. Usually middle range of binder level considered in this study are more suitable for the application whereas higher binder level is more suitable where mold/core experiences much higher head pressure as for example in centrifugal casting process of making cast iron pipes.

The TDT is performed for 90 seconds and LD and RD are sampled at a rate of 10 Hz. Therefore, each LD and RD time-series consists of 900 attributes (variables) each. In total, each observation of the TDT consists of 1800 attributes (LD and RD).

Principal Component Analysis

TDCs contain an immense amount of information regarding the behavior of a given sand system. To detect shifts (using TDCs) in a sand system requires identifying, extracting, and monitoring key TDC features. For this study, the TDC features that will be monitored are obtained through PCA. PCA is a widely used multivariate statistics tool for dimension reduction and feature extraction. PCA has been used for numerous applications. For instance, in the automotive industry, Wells et al. (2012) used PCA to visualize variation patterns in body-in-white assemblies. As another example, PCA has been used to detect and diagnose processes shifts in sheet metal stamping operations using time-series tonnage data (Jin and Shi, 2000).

Briefly, PCA transforms a set of correlated variables into a set of linearly uncorrelated variables. Typically, only a small subset of these uncorrelated variables, called principal components (PCs), are needed to describe systematic process variation and the remainder of the PCs merely reflect statistical noise. In this study, the main (significant) PCs will be extracted as features from TDC curves and will be monitored using a multivariate T^2 control chart. It should be noted that the use of a T^2 chart in conjunction with PCA is a very common procedure in statistical process control (SPC). Readers may refer to Jackson (2005) for further reading to learn more about the use of PCA in SPC.

Detecting Sand System Changes using PCA

The development and implementation of an SPC system requires in-control data. For this study, one of the six sand systems is chosen as the in-control system. Therefore, this study will determine the ability to detect a shift from one sand system to another.

There are fifteen observations for each sand system. In this study, samples were collected in sizes of three $(n = 3)$ and three samples were chosen as historical data for developing control limits $(m = 3)$, which is a total of nine historical observations. These nine historical observations were used to perform PCA. The number of principal components (PCs) that were retained from the PCA was chosen based upon the amount of variance those PCs represented.

In addition to the use of PCs, the Q-statistic was also included in this study. The Q-statistic is commonly used in PCA as it is the measure of the residual (difference) between a data modeled through PCs and the original data. The use of the Q-statistic often provides enhanced shift detection capability, specifically when a shift does not significantly affect the retained PCs (Jackson, 2005).

$$Q = x_i (I - PP^T) x_i^T$$

Where, x_i = i^{th} row of sample, i.e. all observations for sample i,

P = matrix of PCs retained in the model

For each observation of the TDT, the PCs and the Q-statistic, for that tested specimen, were considered as a multivariate observation and monitoring as a Hotelling T^2 statistic. The Hotelling $T^2$was proposed by Harold Hotelling in 1947 and is called Hotelling T^2. The Hotelling T^2 is the multivariate counterpart of the Student's-t statistic.

The T^2 distance is a constant multiplied by a quadratic form. This quadratic form is obtained by multiplying the following three quantities.

1. The vector of deviations between the observations and the mean, $\bar{X}$, which is expressed by $(X - \bar{X})^T$,
2. The inverse of the covariance matrix, S^{-1}, and
3. The vector of deviations, $(X - \bar{X})$.

In general, the higher the T^2 value, the more distant is the observation from the mean. The formula for computing the T^2 is:

$$T^2 = c(X - \bar{X})^T S^{-1}(X - \bar{X})$$

The constant c is the sample size from which the covariance matrix was estimated. The T^2 distances can be plotted to graphical displays and as a result the T^2 chart is the most popular among the multivariate control charts.

It should be noted that the Phase II upper control limit (there is no lower control limit for the T^2) was calculated as

$$UCL = \frac{p(m+1)(n-1)}{mn-m-p+1} F_{\alpha,p,mn-m-p+1},$$

where, $\alpha = 0.0027p$ as suggested by national institute of standards and technology and p is the dimension of the multivariate statistic (i.e., number of retained PCs plus one (for the Q-statistic)).

Since one sand system is considered the in-control system, there are five out-of-control sand systems. The ability of the developed T^2 chart to detect these shifts will be assessed separately in five control charts (i.e., one control chart for every shift to another sand system). Each control chart will consist of seven T^2 samples. The first two samples are the in-control sand system samples that were not used in PCA nor in the development of the control chart's upper control limit. The last five samples of each control chart will be the five out-of-control samples obtained from the 15 out-of-control observations($n = 3$).

Results and Discussion

Figure 44 and Figure 45 show TDT results for each sand system, averaged over all 15 specimens, in the form of LD and RD TDCs, respectively. These average curves show that LD and RD for sand systems 1, 2, and 3 are significantly different from each other. In contrast, the average curves show that LD and RD for sand systems 4, 5, and 6 are quite similar but still distinguishable. Furthermore, as a group; sand systems 4, 5, and 6 are significantly different from sand systems 1, 2, and 3.

Further analysis shows that all the sand system 1, 2, and 3 specimens cracked, and three specimens of sand system 4 cracked during TDT. This is evident from the sudden increase in the average RD curves for sand systems 1, 2, 3, and 4.

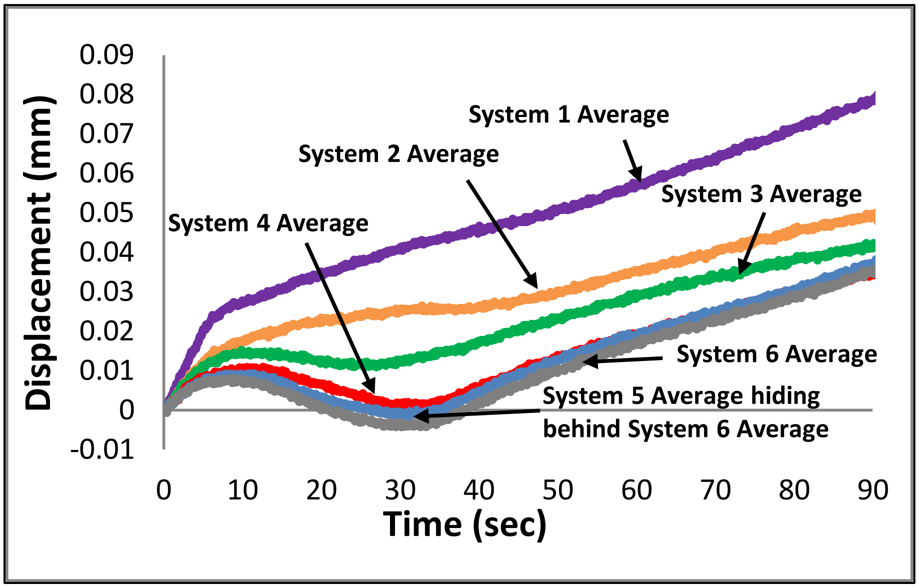


Figure 44. Average LD Curves for Sand Systems

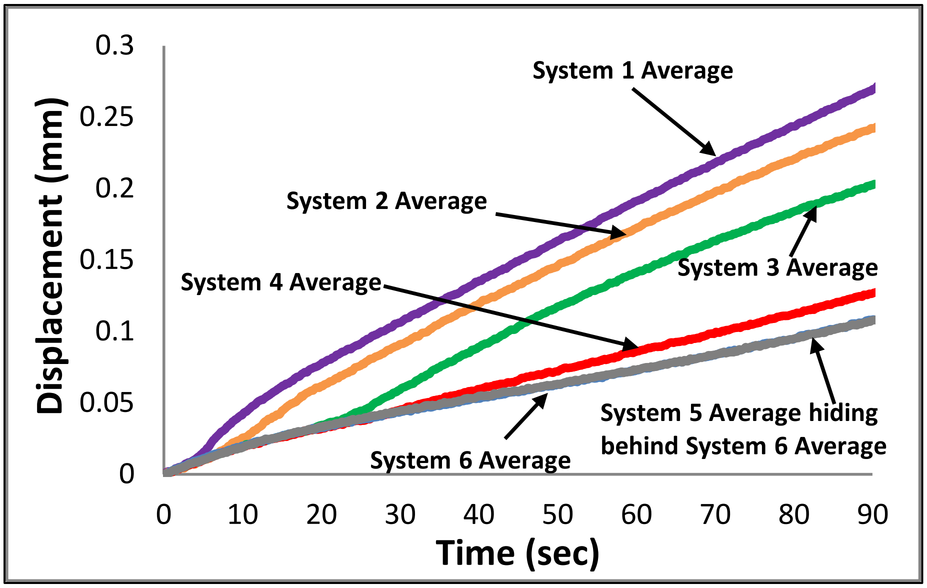


Figure 45. Average RD Curves for Sand Systems

While the average curves sand systems 4, 5, and 6 are distinguishable, this cannot be said for the individual observation of these systems. For example, Figure 46 shows five (of the 15) individual LD curves for both sand systems 4 and 5. From this figure, it is very difficult to distinguish between the two systems. Figure 47 shows five (of the 15) individual RD curves for sand systems 4 and 5. Similarly, it is very difficult to distinguish between these sand systems. However, three sand system 4 curves are distinguishable due to (radial) cracks that occur at approximately 30 seconds. It should be noted that before these cracks occur, the systems are indistinguishable.

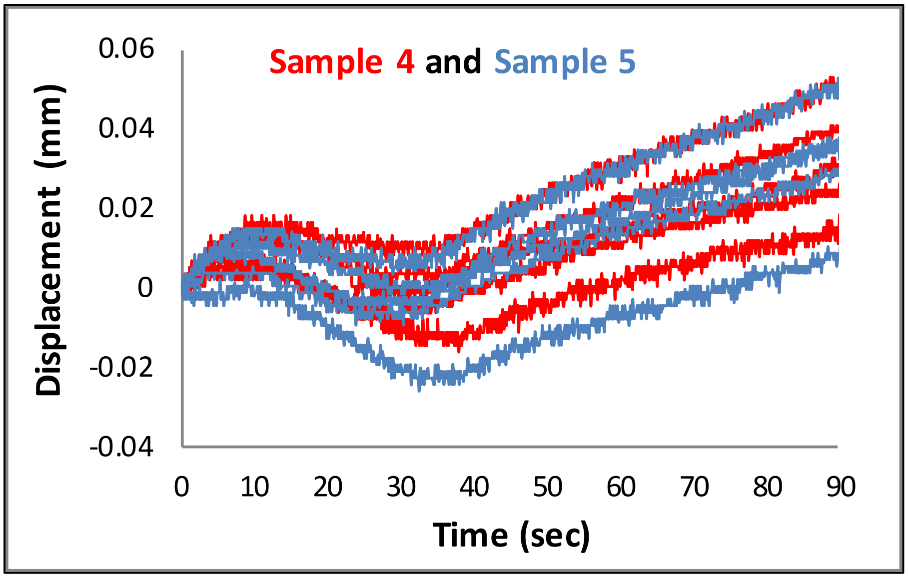


Figure 46. Individual LD Curves for Systems 4 and 5

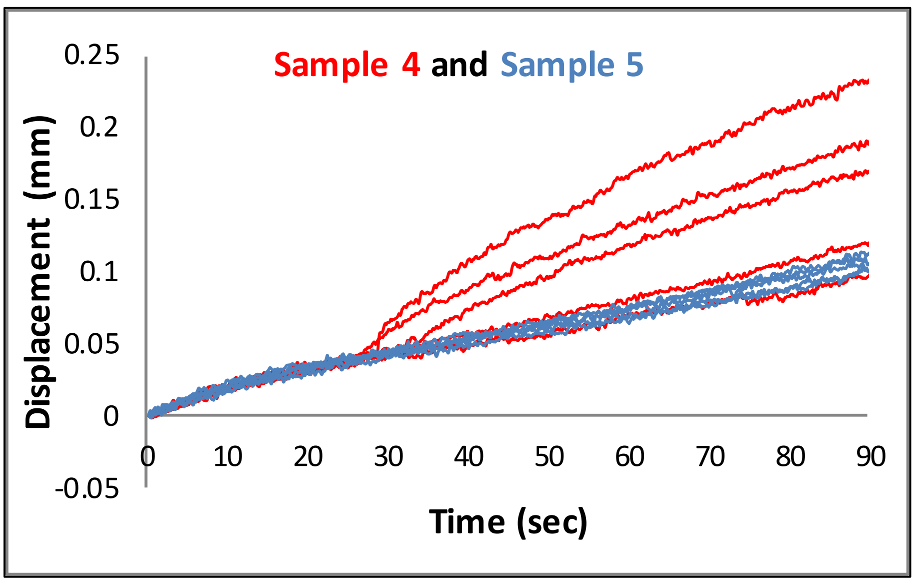


Figure 47. Individual RD Curves for Systems 4 and 5

Similar to the comparisons done from Figure 46 and Figure 47 between sand systems 4 and 5, Figure 48 and Figure 49 compare sand systems 5 and 6. The only difference is that no cracking occurs in any of the 30 observations taken for systems 5 and 6.

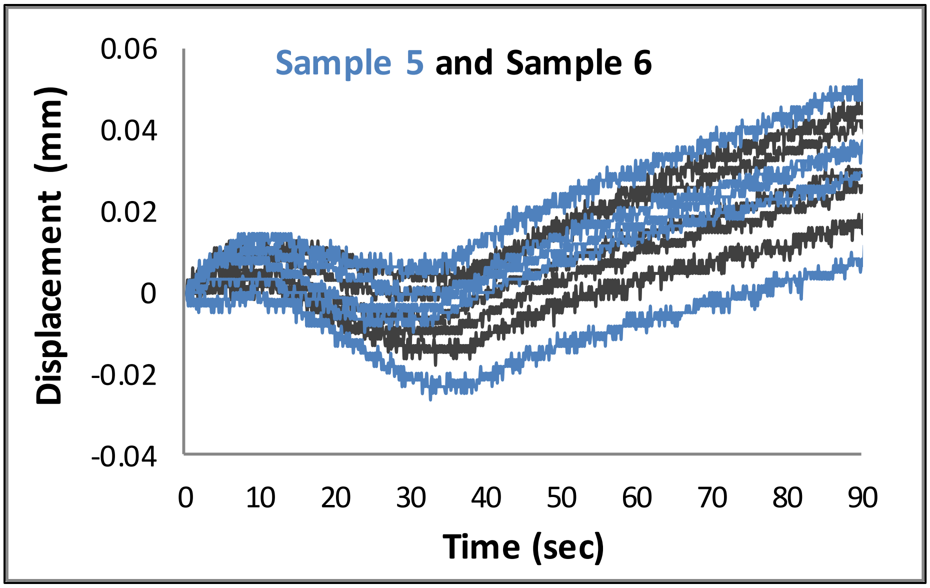


Figure 48. Individual LD Curves for Systems 5 and 6

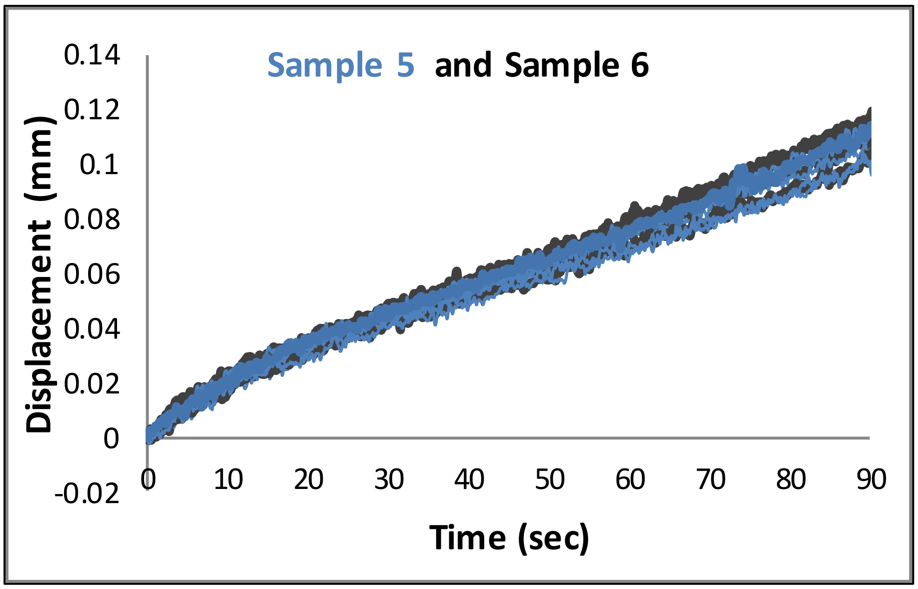


Figure 49. Individual RD Curves for Systems 5 and 6

For this study, one of these sand systems must be considered the in-control system. Specifically, sand system 5 is chosen to represent the in-control system for following two reasons.

1. Sand system 5 is both very similar to and very different from other sand systems tested in this study. This allows understanding the control chart's performance across a wider spectrum of shifts.
2. Sand system 5 samples experienced no detectable cracking during TDT.

It is important to mention that the TDT parameters used in this study are suitable for sand systems with lower binder level. If sand system 1 or 2 has been considered as in-control sand system, it would have been easy to detect an out-of-control sand system as TDCs for these systems are noticeably different than any other sand systems.

After sand system 5 was determined as in-control, PC model was developed using samples sizes of three ($n = 3$) and three samples were chosen as historical data for developing control limits ($m = 3$), which is a total of nine historical observations of sand system 5. PC model was applied to all the observations of sand systems 1 through 6 to collect 4 PCs that represent 97.4% variance of the data set. Figure 50 to Figure 54 show T^2 control charts for the scenarios of shifting from sand system 5 to sand systems 1, 2, 3, 4, and 6, respectively.

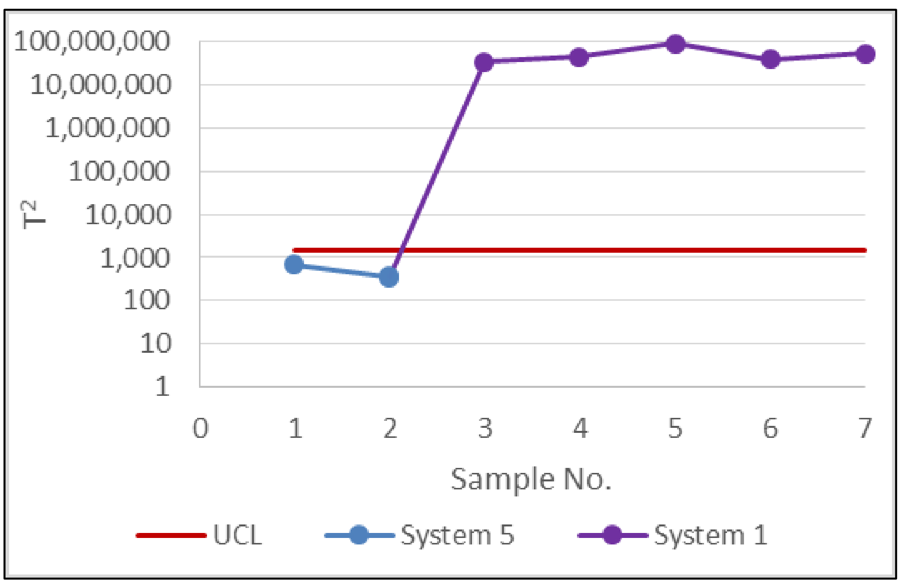


Figure 50. Control Chart for Systems 5 and 1

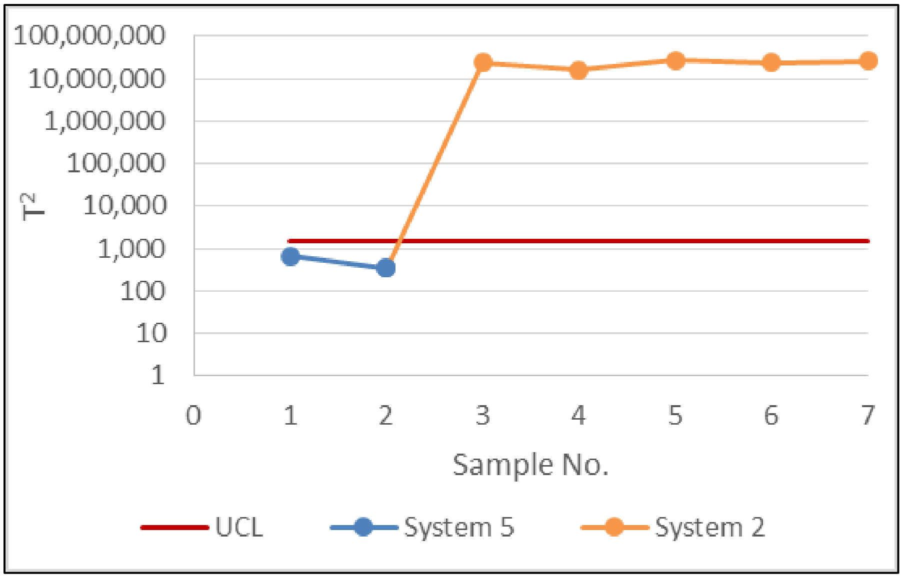


Figure 51. Control Chart for Systems 5 and 2

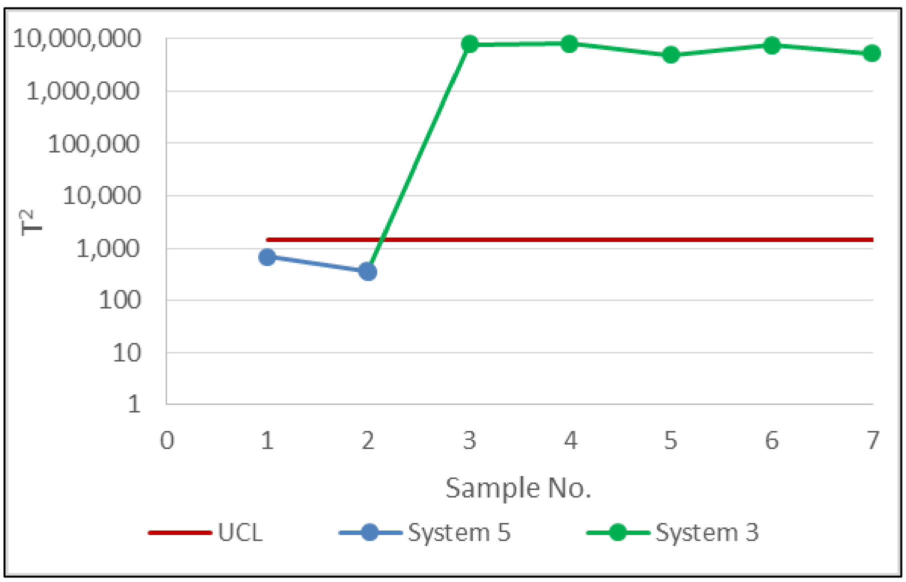


Figure 52. Control Chart for Systems 5 and 3

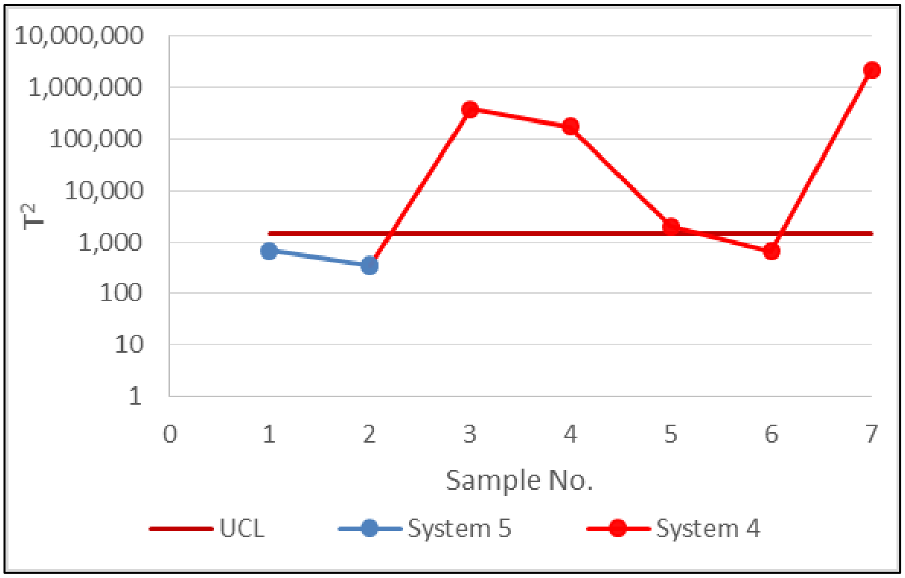


Figure 53. Control Chart for Systems 5 and 4

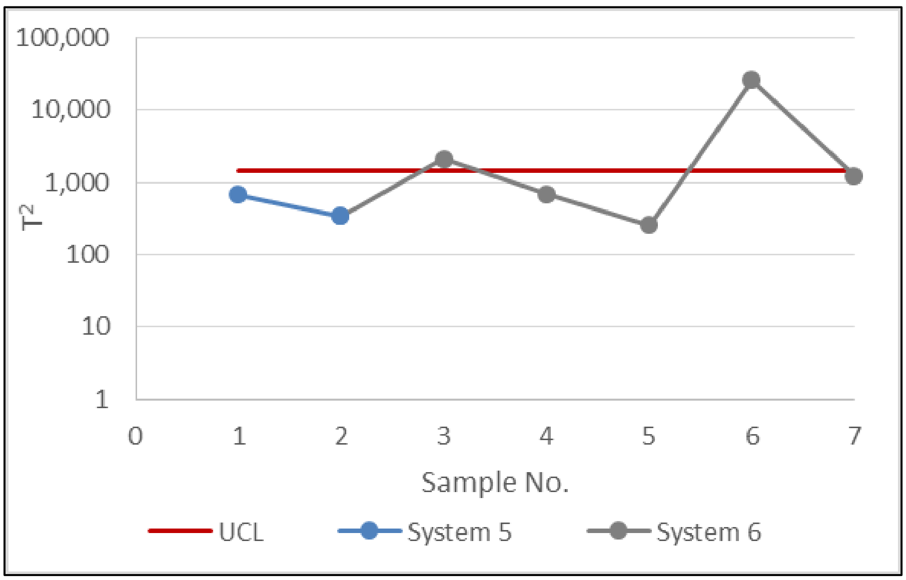


Figure 54. Control Chart for Systems 5 and 6

These control charts show that systems 1, 2, and 3 can be easily and correctly identified as out-of-control. For sand system 4, it takes about 1 and a half samples on average to correctly identify a process shift. In other words, on average 6 observations are required to detect this change. Similarly, for system 6, it takes about 2 and a half samples on average to correctly identify a process shift which means on the average 7.5 observations are required to detect this change. TDT has demonstrated the beneficial strategy for detecting shifts in Shell RCS. This was possible using more advanced analytical methods, such as PCA.

Conclusion

From the results of this study, it can be concluded that the SPC method using PCA can be very useful in detecting shifts in chemically bonded sand systems. It will be more interesting to apply this type of SPC method in a working foundry to monitor a chemically bonded sand in real-time at line speed. Results of this study show that this strategy can detect a change in sand system using at most 7.5 observations (on average). In other words, foundry can detect a change in a sand system by testing 7.5 disc-shaped specimens on average each of which may represent a mold from production line.

TDT provides coupled thermo-mechanical behavior of sand system at steady state temperature and head pressure that can be adjusted to represent actual casting scenario. SPC method presented in this study inherently incorporate coupled thermo-mechanical behavior of sand system as it considers time-series data from TDT, it is believed that this SPC method can detect wide range of process shifts in sand systems. Many foundries attempted to provide disc-shaped specimens from their production line for this study, however, the quality of the disc-shaped specimen was a major concern as foundries do not have an effective way to produce a disc-shaped specimen along with production of a mold/core. In future, when this will not be a concern, it would be fascinating to apply this SPC method to detect process shift in working foundries.

CHAPTER IV

QUALIFICATION OF CHEMICALLY BONDED SAND SYSTEMS

The objective of this phase of research is to implement a quality control framework that can be used to monitor quality of the castings. In following section, a quality control framework is proposed that a foundry can use to monitor their chemically bonded sand system. The use of this framework will be demonstrated through a case study.

Quality Control Framework

The recommended quality control framework is shown in Figure 55. In addition to the SPC method (using PCA) used in previous chapter, casting trial is included in this framework as a qualification technique for a sand system. Results of casting trial will help to determine whether the change in sand system will affect the quality of the casting or not. The proposed quality control framework can help foundries through a systematic process to administer a mold/core making process.

It is important to mention that the framework only considers defects caused by sand system and assumes that other factors such as improper pattern or tool design, improper gating design, improper melting and pouring practices, and improper metal composition etc. are non-existent. For this framework, it is considered that these other factors are constant. This framework mainly focuses to verify the effect of a change in sand system on casting quality.

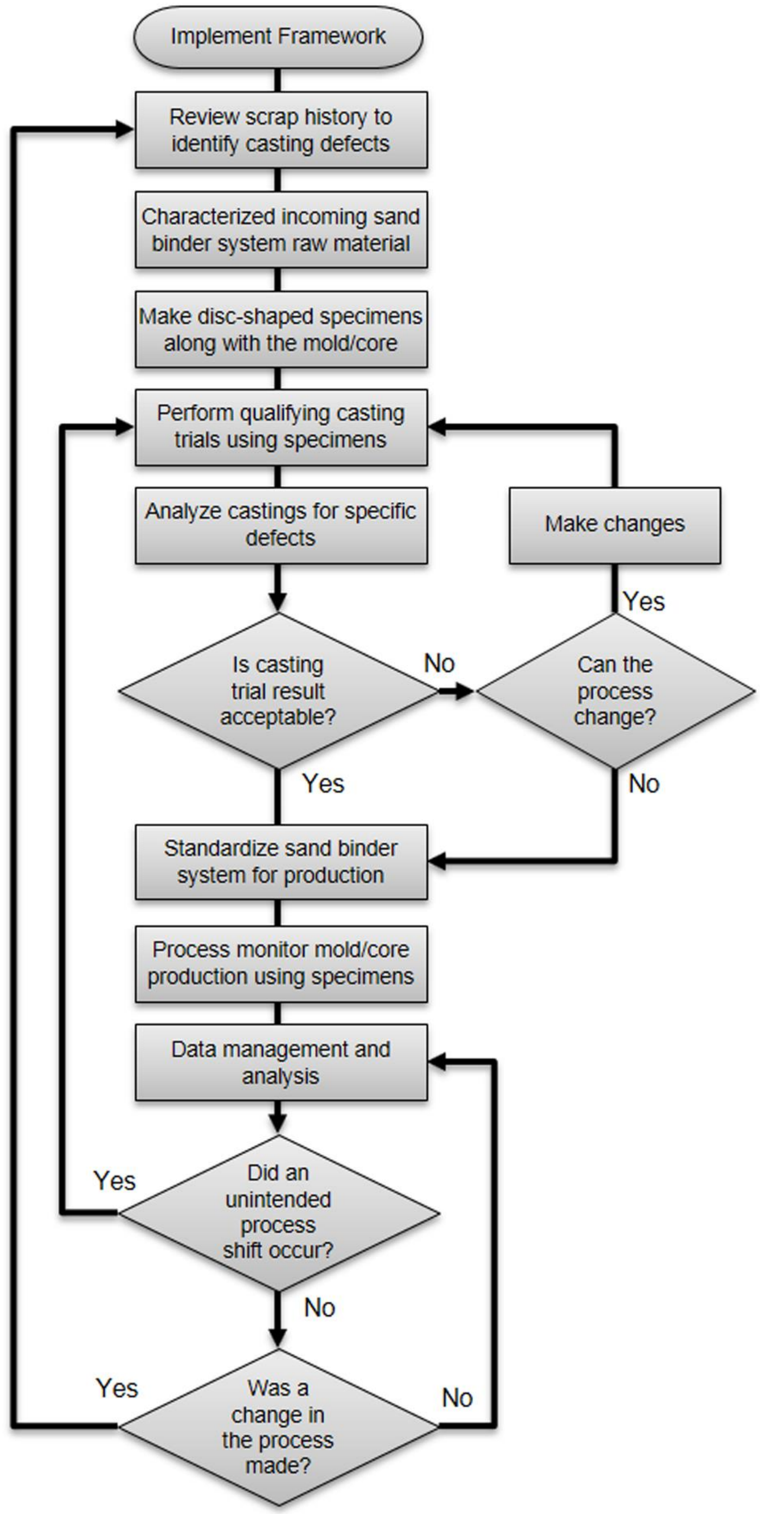


Figure 55. The Quality Control Framework

The quality control framework is explained through following steps. The idea is to qualify a chemically bonded sand system for given alloy, metallostatic pressure head, temperature and minimum section thickness of the mold/core using disc-shaped specimen tests and then use SPC that uses the TDCs to identify any shift in a sand system.

1. Review casting scrap history and identify primary casting defects at the mold-metal-interface.

   This is to consider historical quality data that will help a foundry to identify a most occurring casting defect such as veining penetration, distortion, erosion, cuts, washes and gas that can be caused due to sand system. In the study, only a casting surface related defect (veining and penetration) will be considered as diagnostic casting trial for other defects are still under development.

2. Status monitoring of Incoming Materials
   a. GFN and screen distribution
   b. Sand grain shape
   c. LOI etc.

   This is to characterize the incoming raw material of a sand system and to identify any change in raw material as early as possible.

3. Qualifying Casting Trial
   a. Surface Defect Model
   b. Distortion Model
   c. Erosion Model
   d. Gas Model

Casting trial using disc-shaped specimens should be performed to observe the casting surface that can be expected from current sand system under given test parameters like pouring temperature, head-pressure, and metal chemistry.

4. Analyze the casting surface and standardize a minimum section thickness (8 mm is nominal) that handles the fill temperature, head-pressure and chemistry

   If a foundry is getting acceptable casting surface for the tested disc-shaped specimen during a casting trial then it is suggested that foundry accepts the sand system for given fill temperature, head-pressure and chemistry.

5. Process Monitoring using disc-shaped specimens produced with production cores/molds

   Foundries can use disc-shaped specimen laboratory tests to perform process monitoring of a mold/core making process to identify a shift in a process. Specifically, monitoring sand system using SPC method with PCA may eliminate necessity to use several of these disc-shaped specimen tests and may only require foundries to use the TDT.

6. Data management and analysis system gathers data from casting scrap, monitoring incoming materials and process

   Record all these data in to a data management system where it can be stored and analyzed to study the effect of a change in a sand system on casting rejections. It can be a database to compare different sand systems and related rejections. In addition, when foundry experience a change in sand system that has been occurred previously in time, then foundry can look back into the data analytic system to identify how it can affect rejections and take decision based on statistics. For this purpose, a separate software can be developed in future that will help foundries to manage their data, detect trends, and make correct decisions.

7. Process Shift requires a new Diagnostic

If a new process shift occurs, then it will require a new diagnostic casting trial to observe the effect of this change on casting quality. Casting trial used in this step will keep all other casting parameters such as metal chemistry, pouring temperature, and height of pouring etc. constant. If casting trial generates acceptable casting result, then a foundry is sure that the tested sand system will not deteriorate the quality of the casting. Further, after acceptable casting results if foundry gets worse quality in their actual production then it suggests that foundry need to investigate other factors such as improper pattern or tool design, improper gating design, improper melting and pouring practices, and improper metal composition etc. for possible reasons.

Following case study demonstrate the application of the quality control framework to represent real-world situation.

Case Study

The importance of the quality control framework is exemplified through a case study. In this study, three sand systems with similar sand type (round grain silica), binder type and binder level (3% resin coated shell) were considered. The only difference between these systems is the origin of sand. The sand used in this study are 60 GFN sands from Wedron, Unimin, and Badger. Location of Wedron and Unimin is about 65 miles away from each other, while location of Badger is about 140 miles away from Unimin and about 170 miles away from Wedron. Foundries may use these sands interchangeably as these three sands are very similar to each other i.e. silica content, grain fineness (60 AFS-GFN sands were considered in this study), grain shape etc. are identical. The resin coated sands for these three sands were prepared in the same binder coating facility using the same binder type, similar binder and additives level to avoid any inconsistencies. These sands were considered to represent batch-to-batch variability in sand system in working foundries.

The purpose of this study is to demonstrate the usefulness of the SPC method using PCA in detecting differences between these sand systems and illustrate the use of casting trial to verify the casting surface quality for these sand systems.

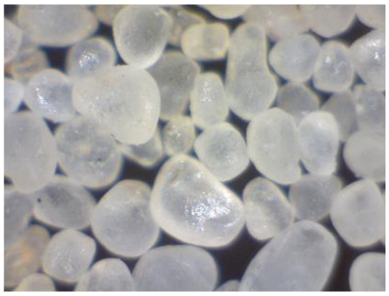
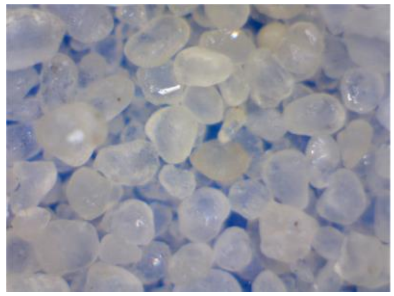
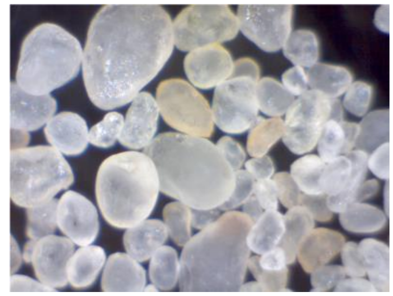
Sand Systems

Table 11 shows the percentage sand retained in GFN for the three sand systems. GFN results suggest that all the three sands are similar in size which is AFS-GFN 60. In addition, shape of sand particles is also alike which can be seen in Table *12*. The results suggest that differences between these sands are very little.

Table 11. Percentage Sand Retained in GFN for Sand Systems

System / Sieve	Wedron	Unimin	Badger
6	0	0	0
12	0	0	0
20	0	0	0
30	0.1	0.1	0.1
40	2.5	2.7	6.0
50	22.5	23.1	17.6
70	36.2	34.0	29.9
100	25.8	26.5	35.8
140	11.3	11.7	9.3
200	1.5	1.8	1.2
270	0.1	0.1	0.1
PAN	0	0	0

Table 12. Microscopic Image of Sand Particles

Wedron	Unimin	Badger
		

These sands were coated with phenolic novolac resin at 3% binder level. The resin coating was done at one of the sand binder supplier's laboratories (whose identity is kept anonymous), where these three sands were treated similarly to make sure that there is no variation due to the coating process. Disc-shaped specimens were made at WMU's laboratory using supplier recommended parameters 250°C and 40 seconds.

Detecting Sand System Changes

Hot tensile strength test, which is the commonly used AFS standardized test most foundries in the USA uses to monitor their sand system, was performed on these three sand systems. Historical data (sand binder supplier provided) suggest that the hot tensile strength for Wedron 3% RCS should be between 300-450 psi. Results of the hot tensile strength are shown in Table 13.

Table 13. Hot Tensile Strength Test Results

3% RCS	Hot tensile strength (psi)			
Wedron	335	322	425	390
Unimin	330	352	355	375
Badger	410	320	430	330

Analysis of variance was performed on these hot tensile strength test results to determine whether their mean differ or not. Figure 56 shows the interval plot for hot tensile strength for Wedron, Unimin, and Badger sand systems. Interval plot shows that 95% confidence interval of these three sand systems overlap on each other. As p-value for the three pairwise comparison is greater than 0.05, there is not enough evidence to conclude that hot tensile strength for the three sand systems are significantly different.

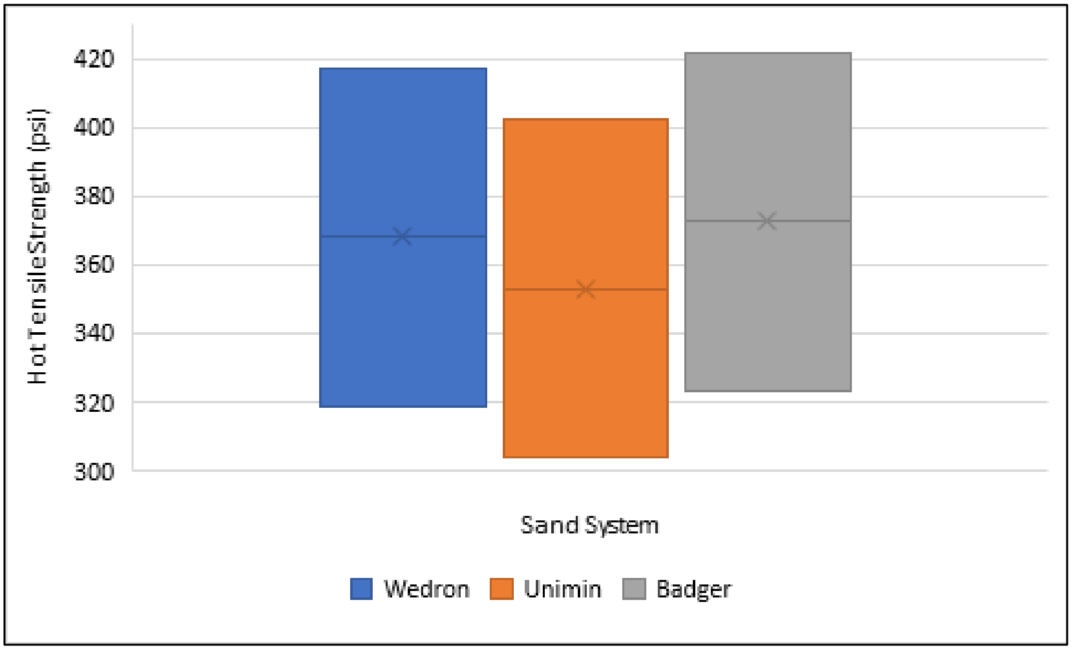


Figure 56. Interval Plot of Hot Tensile Strength for Wedron, Unimin, and Badger

Results of this analysis suggest that the hot tensile strength is not capable to discriminate between these three sand systems. This shows that foundries which are using hot tensile strength test to monitor their sand system will not be able to distinguish between the changes in sand. However, effect of this change in sand system affects casting quality or not is a separate concern.

Subsequently, disc-shaped specimens were made for these sand systems using the same parameters 250°C (482°F) and 40 seconds and TDT was performed on these specimens. For

TDT, five test settings (combination of temperature and pressure), as shown in Table 14, were considered to find the optimal test setting that can quickly detect a change in these sand systems.

Table 14. TDT Settings

Test Setting	Temperature (°C)	Pressure (N)
1	750	3.5
2	750	5.5
3	850	4.5
4	950	3.5
5	950	5.5

In this study, Wedron is considered as in-control sand system because, the available quantity of this sand systems was greater than Unimin and Badger sand systems. Initially, it was planned to perform TDT on 30 specimens for the in-control sand system and 5-5 specimens for the remaining two sand systems for each TDT setting. During TDT, almost half of the specimens experienced cracks for both Wedron and Unimin. However, specimens of Badger sand did not show tendency to crack. From previous research, it is clear that crack induces large undulation in TDCs which may affect the detection ability of the proposed SPC method. Therefore, all the data of the cracked specimens were disregarded. In addition, because of the limited quantity of these sand systems, 15 observations without cracking (instead of 30) for in-control sand system and 5-5 for the remaining two sand systems were targeted.

Figure 57 to Figure 61 show representative range of longitudinal distortion curves for Wedron 3% RCS at each TDT settings. These curves suggest that as test temperature and pressure increase, variability in LD curves decreases (spread between these curves reduces) for Wedron sand systems. The same is true for Unimin and Badger sand systems as well.

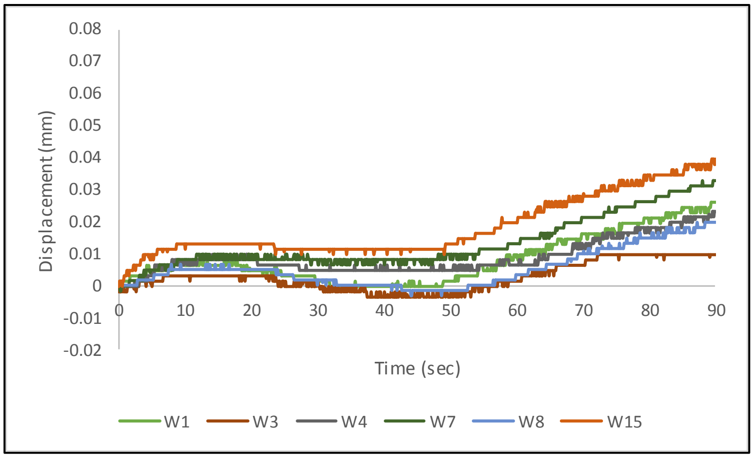


Figure 57. Wedron 3% RCS LD Curves for 750°C 3.5 N TDT Setting

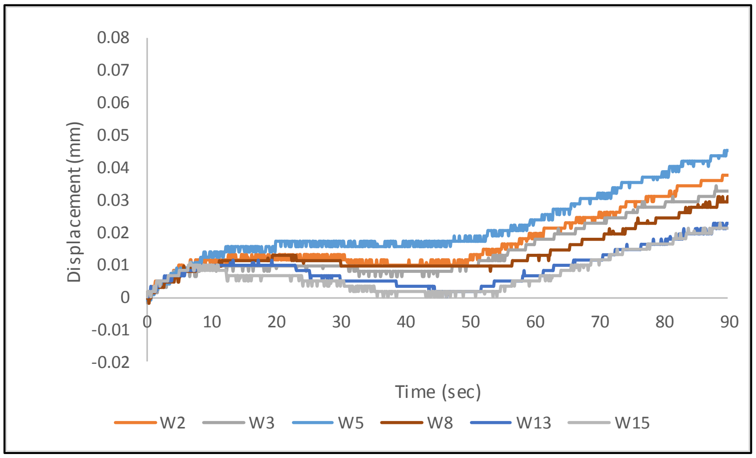


Figure 58. Wedron 3% RCS LD Curves for 750°C 5.5 N TDT Setting

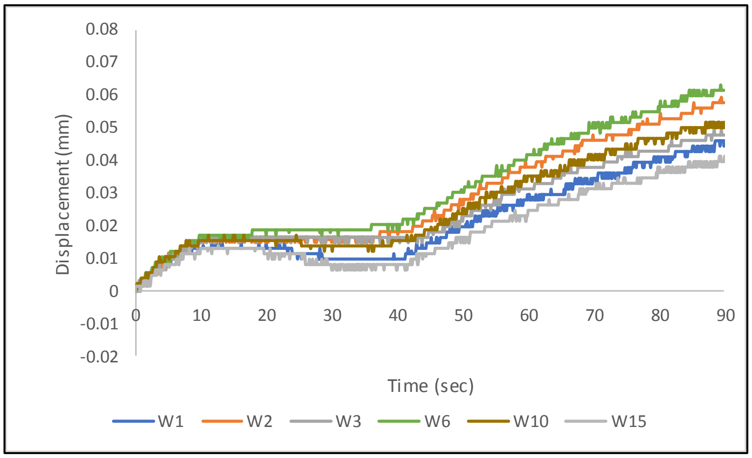


Figure 59. Wedron 3% RCS LD Curves for 850°C 4.5 N TDT Setting

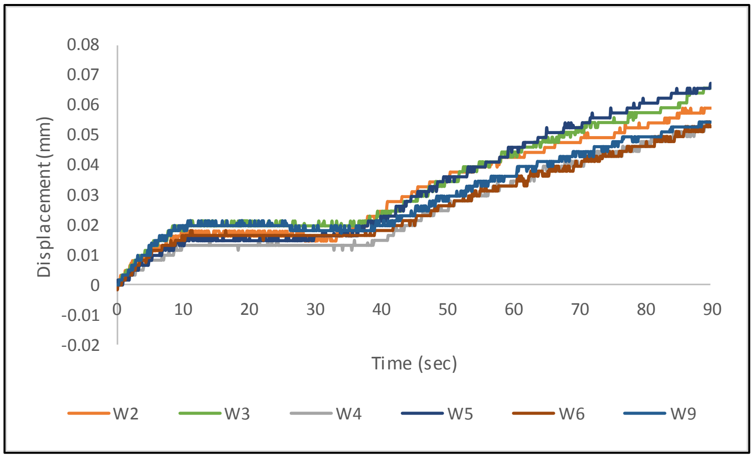


Figure 60. Wedron 3% RCS LD Curves for 950°C 3.5 N TDT Setting

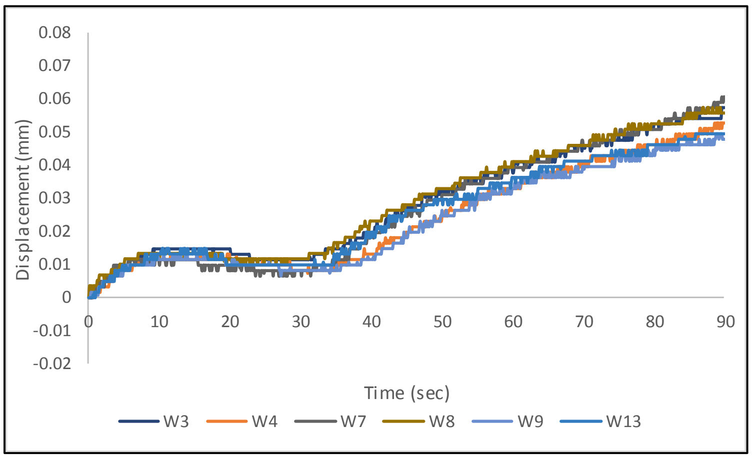


Figure 61. Wedron 3% RCS LD Curves for 950°C 5.5 N TDT Setting

To detect a change, PC model was developed using samples sizes of one $(n = 1)$ and thirteen samples of Wedron sand system were chosen as historical data for developing control limits$(m = 13)$. PC model was applied to two remaining observations of Wedron as well as all the observations of Unimin and Badger sand systems to collect 4 PCs. Figure 62 to Figure 66 show T^2 control charts for the scenarios of shifting from Wedron sand system to Unimin and Badger sand systems at each TDT settings.

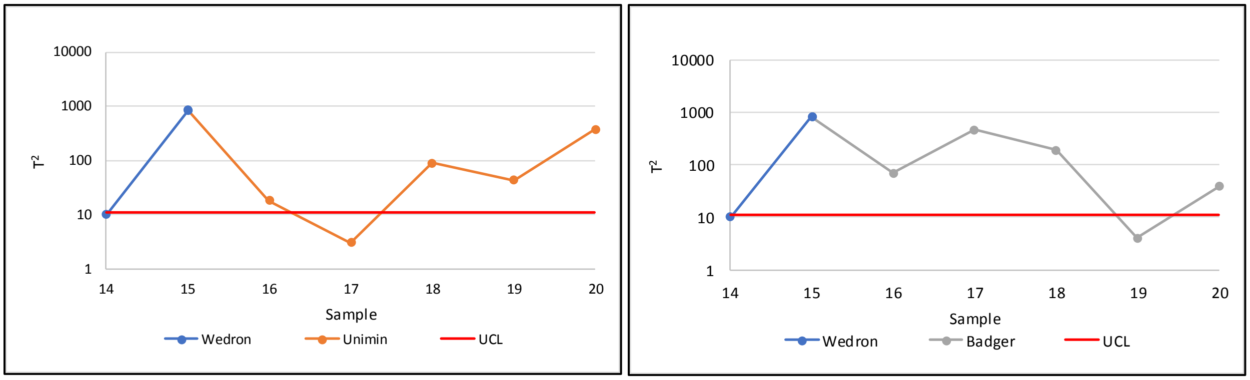


Figure 62. Control Charts for 750°C 3.5 N TDT Setting

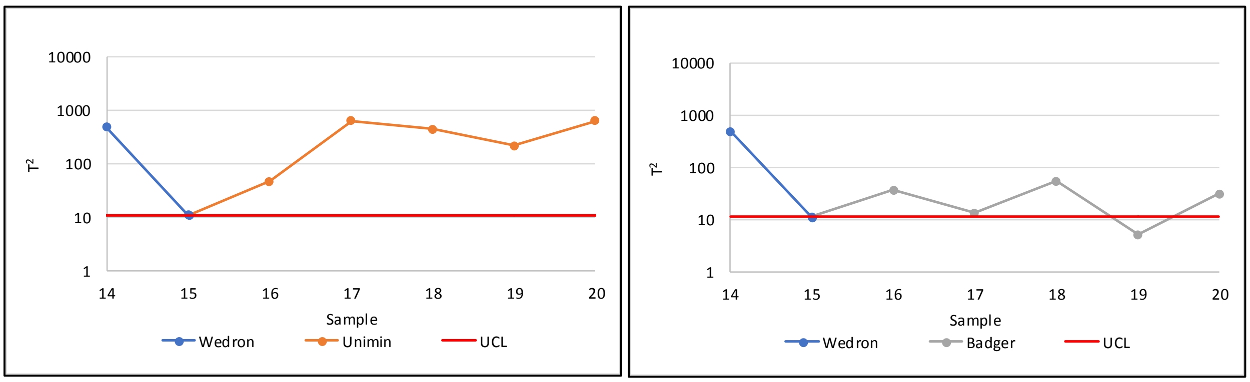


Figure 63. Control Charts for 750°C 5.5 N TDT Setting

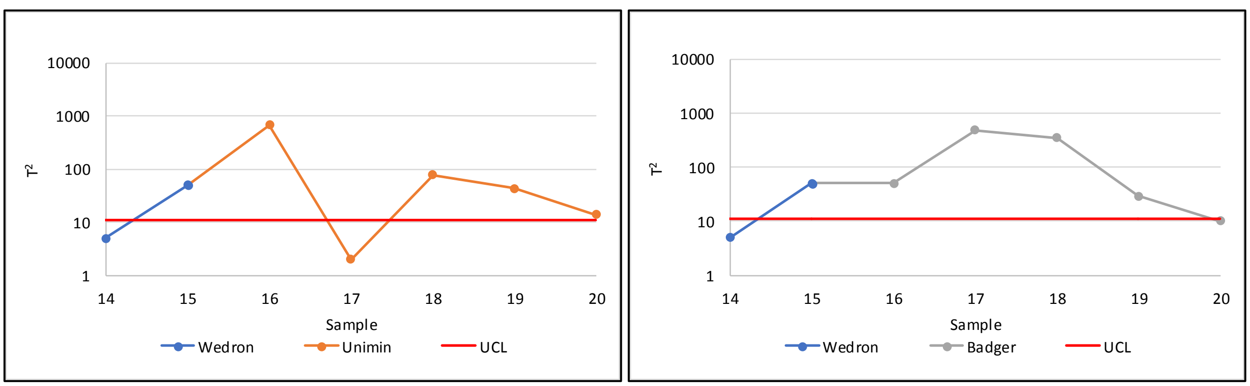
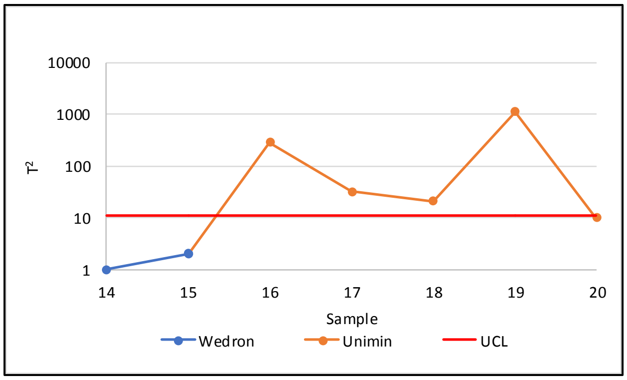


Figure 64. Control Charts for 850°C 4.5 N TDT Setting



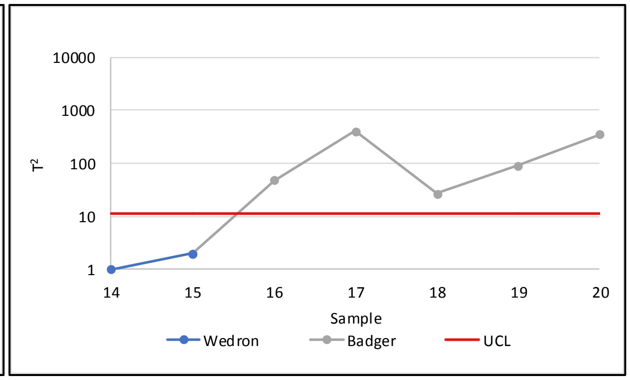
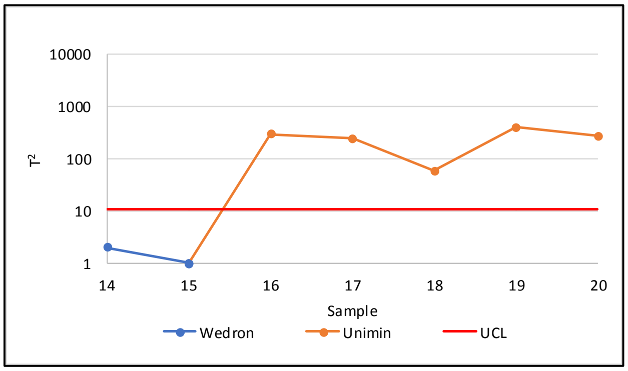


Figure 65. Control Charts for 950°C 3.5 N TDT Setting



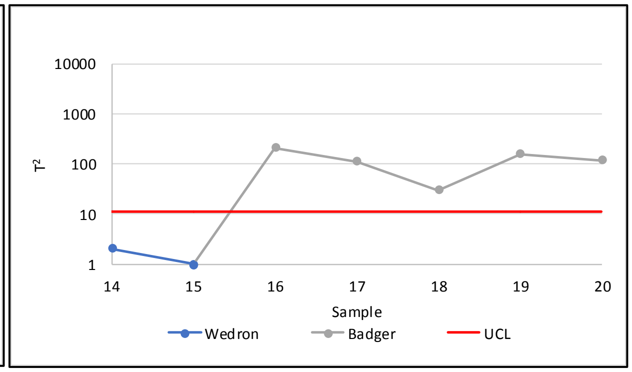


Figure 66. Control Charts for 950°C 3.5 N TDT Setting

In these control charts, as first thirteen samples were considered historical data, sample 14 and 15 are the remaining two samples for Wedron sand system while samples 16 through 20 are for either Unimin or Badger sand system as depicted in control chart.

Control charts suggest that as temperature and pressure increase in TDT, ability to detect a change in sand system increases. For instance, at 950°C TDT settings, control charts correctly identified out-of-control sand systems. It is important to mention that 3% RCS is typically used in foundries to make medium sized iron castings. Usually, TDT is performed to mimic the actual casting process which would be at or above 1350°C and 4.5 N. The results of this study suggest that TDT can be performed at lower temperature than the actual casting process to detect a change in the considered sand system. However, to study the behavior of the sand system under actual casting parameters, it is recommended to perform TDT that mimic the casting process.

Results of this study show that SPC method using PCA can effectively detect a change between these considered sand systems at lower temperature than the actual casting process. It is important to reiterate that the difference between these sands is very subtle and it cannot be detected by conventional hot tensile strength test.

Qualifying Casting Trial

As a next step, to determine the effect of these differences in sand systems on casting quality, casting trials were performed. In this study, two casting trials were performed to evaluate specimen/metal interface for the three chemically bonded sand-binder specimens. In one, aluminum alloy was poured from 6 inch head height, while in second, gray iron was poured from 9 inch head height. Two green sand molds were produced with a pouring sleeve and filter for constant head-pressure and fill velocity. The mold contained twelve cavities with core prints. This approach allowed possible variation in casting quality to be assigned to only disc-shaped core specimens.

In this experiment, three disc-shaped specimens for each of the three sand systems were considered in each casting trials. In addition, three specimens of ceramic sand system were also included as place holder whose casting surface quality was not in interest for this study.

The casting trial procedure consisted of the following steps:

1. Temper the green sand to the desired compactability level in a muller or mixer.
2. Squeeze the sand within the flasks against the matchplates to produce molds.
3. Pour molds.

4. Shake and inspect casting.

Note: All molds were prepared and tested at WMU Metal Casting Laboratory. Ambient conditions were temperature controlled at 20 ± 1°C and relative humidity was controlled at 50 ± 2%.

Preparation of Green Sand: It was important to keep the bonding formulation simple to reduce potential errors in preparing the green sand batch and simplifying the analysis. Apart from sand, clay, and water; no additives were introduced to the green sand systems used in this study. Compactability was monitored continuously, while water additions were raised or lowered to produce the 35% target compactability. The sand was not discharged until the compactability was on target. Thus, the green sand systems used in this study were tempered to a desired compactability and tested for other green sand properties.

The silica base aggregate (lake sand, 62 GFN, 4 screen) used in the study came from Michigan. The green sand system used in the study was mulled (200 kg Simpson Sand Muller) at WMU Metal Casting Laboratory. The green sand system used a clay bond pre-blend made up of 20% Southern Bentonite / 80% Western Bentonite where total clay added was 8.0% BOS (methylene blue clay was 7.45%), and water added to produce the desired compactability.

Surface Defect Casting Trial: One of the casting trials at WMU investigates surface anomalies and finish at a specimen/metal interface. The so-called surface defect casting trial was used to compare casting surfaces for the three chemically bonded disc-shaped specimens. Veining and penetration are among the most common metal casting surface defects. Therefore, the proposed casting trial aims to qualify against these two surface defects. Ramrattan et al. (2011) and Derrick et al. (2012) identified one important mechanism for veining. The postulation is that one mechanism for veining is stress cracking in the sand system where metal can penetrate. The aim is to wet the surfaces of the disc-shaped specimens while being poured with aluminum and gray iron to a 6 inch and 9 inch head respectively. The purpose of work is to investigate whether variation in sand systems (that represent batch-to-batch variability) affects casting quality or not. Specifically, common casting surface defects, such as penetrations and veining on the surface can be related to thermal-mechanical issues measured by TDTs. The CAD representation of this surface defect casting trial for multiple specimens under the same metallostatic pressure is shown in Figure 14 (Chapter 1).

Procedure: Green sand cope and drag mold halves were fabricated according to an experimental matchplate pattern, shown in Figure 67. The chemically bonded disc-shaped specimens set on core prints in the drag mold are pictured in Figure 68. The gating was a central 6 inch and 9 inch sprue pouring sleeve fitted with an appropriate filter prior to the gate for wetting specimen surfaces.

Figure 67. Matchplate Pattern for the Surface Defect Casting Trial.

Figure 68. The Disc-shaped Specimens Placed on the Core Prints in the Drag Half of the Mold

Melting and Pouring: The molds were poured where the chemically bonded disc- shaped specimens were placed randomly. The sand-to-metal weight ratio for all molds was 2:1. The molds were manually poured (temperature at pour ladle was 700 ºC (1292 ºF) for aluminum and 1427ºC (2600ºF) for gray iron) and molten metal was delivered through a direct pouring sleeve fitted with a ceramic filter. The molds were poured to a 6 inch head height for aluminum and a 9 inch head height for gray iron. The metal chemistry is shown in Table 15 and Table 16.

Table 15. Gray Iron Chemistry

C	Mn	P	Si	Cr	S	Al	Pb	Ti	Mo	Cu	Ni	Sn	Sb	Mg	Fe
3.59	.65	.097	2.39	.103	.101	.001	<.001	.011	.02	.13	.06	.009	.002	.0025	92.94

Table 16. Aluminum Chemistry

AL	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Ca	Cd	Na	Pb	Sr
92.2	7.07	0.16	0.05	0.02	0.33	0.007	0.006	0.02	0.10	0.0007	0.002	0.001	0.02	0.01

The molds were prepared and poured at WMU Metal Casting Laboratory. The castings were allowed to solidify by air-cooling prior to shake-out and sectioned near the specimen/metal interfaces.

Data Collection and Observation: Disc-shaped specimens used in casting trials were destroyed or damaged, so no direct observations could be made from those surfaces. Observations from the surface defect casting trial were made after the castings were solidified, shaken-out, and sectioned at the specimen/metal interface. Data were then collected using the Keyence 3D-Macroscope (VR-3100). Surface roughness, Ra µm of the as-cast metal interfaces were obtained for the comparison. Table 17 and Table 18 show the results of surface roughness for the sectioned surfaces of the aluminum and gray iron castings respectively. As three disc-shaped specimens were used for each sand systems, surface roughness of the six surfaces are recorded.

Table 17. Aluminum Casting Surface Roughness

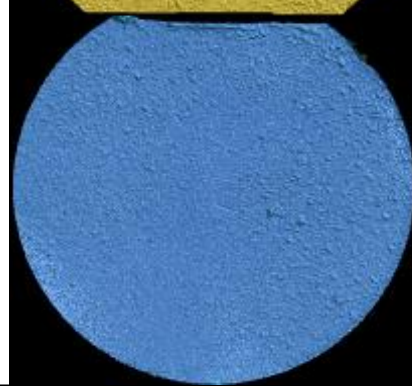
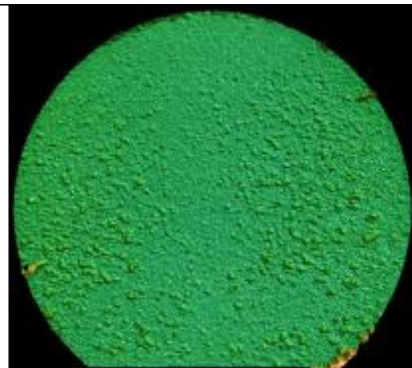
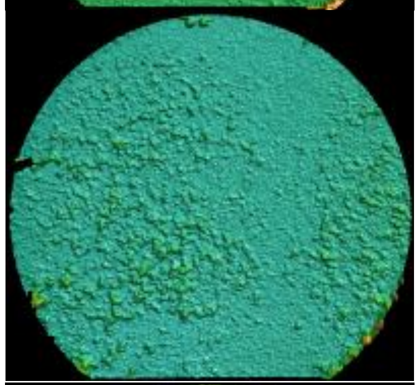
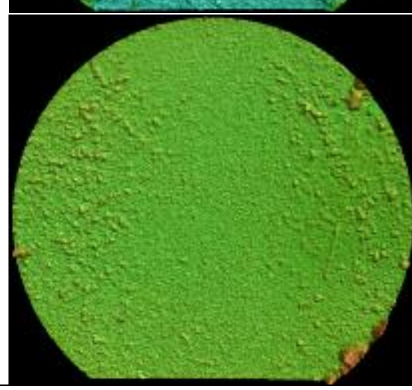
Sand System	Keyence 3D-Macroscope Image of Casting surface	Surface Roughness Sa (μm) for six surfaces
Wedron		24.5, 21.4, 23.3, 21.2, 20.0, 31.0
Unimin		20.3, 26.6, 25.0, 20.4 22.0, 24.4
Badger		27.4, 22.3, 27.1, 29.1, 17.4, 19.2

Table 18. Gray Iron Casting Surface Roughness

Sand System	Keyence 3D-Macroscope Image of Casting surface	Surface Roughness Sa (μm) for six surfaces
Wedron		65.8, 63.1, 69.5, 64.2, 60.1, 64.0
Unimin		110.2, 110.1, 104.0, 112.6, 109.0, 102.1
Badger		56.4, 56.0, 58.1, 49.2, 55.9, 51.3

Analysis of variance (ANOVA) was performed on surface roughness to compare between the three sand systems. For this, Minitab software is used and significance level 0.05 is considered. For aluminum casting trial, ANOVA results (Table 19) show that there is no significant difference between casting surface roughness for the three sand system. Interval plot of surface roughness of the aluminum castings for the three sand systems are shown in Figure 69. However, for gray iron casting trial, ANOVA results (Table 20) show that casting surface roughness of the three sand systems are significantly different. For further detail, Tukey pairwise comparison was also performed simultaneously. Results of this analysis is shown in Table 20.

Table 19. Results of ANOVA for Surface Roughness of Aluminum Casting Trial

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	2	1.274	0.6372	0.04	0.959
Error	15	229.397	15.2931		
Total	17	230.671			

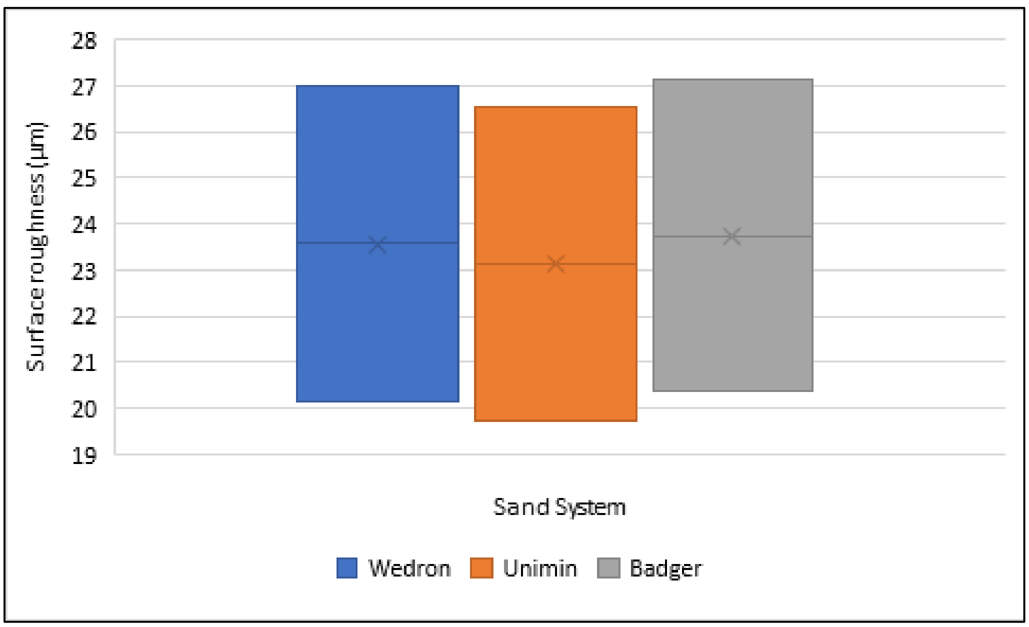


Figure 69. Interval Plot of Surface Roughness for Aluminum Casting Trial

Table 20. Results of ANOVA for Surface Roughness of Gray Iron Casting Trial

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Factor	2	9719.9	4859.97	384.36	0.000
Error	15	189.7	12.64		
Total	17	9909.6			

Tukey Pairwise Comparisons

Grouping Information Using the Tukey Method and 95% Confidence

Factor	N	Mean	Grouping		
Unimin	6	108.00	A		
Wedron	6	64.45		B	
Badger	6	54.48			C

Means that do not share a letter are significantly different.

Figure 70 shows an interval plot for surface roughness of gray iron castings for the three sand systems. This shows that surface roughness of castings produced by these three sand systems are significantly different. It is important to note that this is only true for the tested alloy chemistry at the tested temperature and head pressure. Use of different alloys and pouring conditions may affect the resulting surface roughness of the castings.

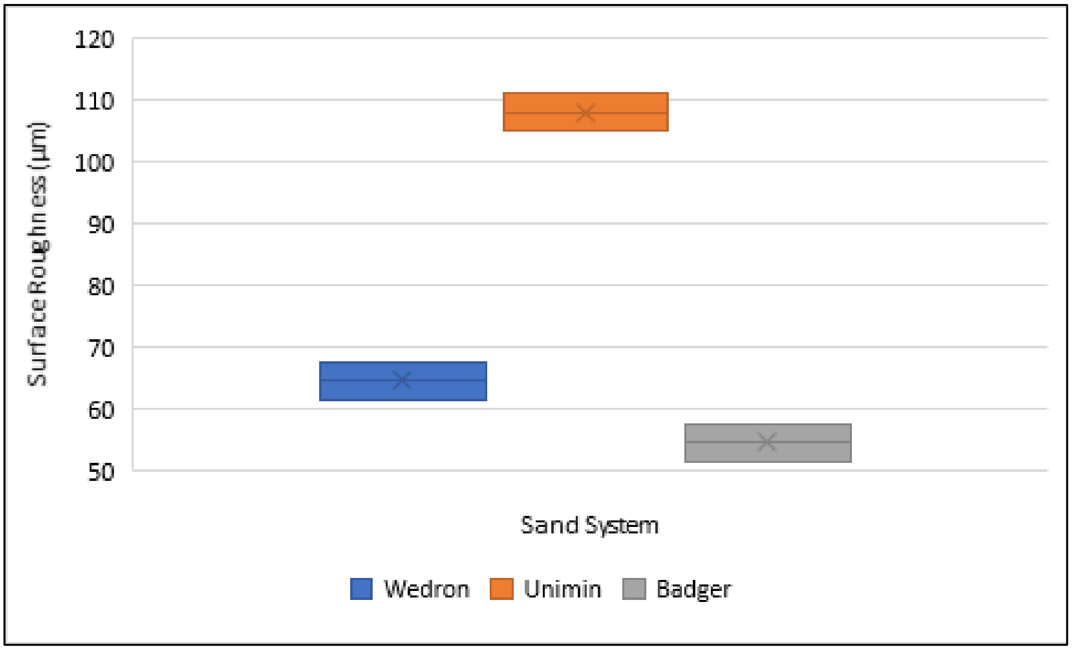


Figure 70. Interval Plot of Surface Roughness for Gray Iron Casting Trial

Conclusion

Results of this analysis show that there are significant differences between the surface roughness of the three sand systems for gray iron casting trial, however, there are not enough evidence to conclude that the casting surfaces are different in case of aluminum casting trial. This research shows that process shifts in sand system do not affect casting quality in case of aluminum casting. In contrast, for gray iron application, a shift in a sand system significantly affect the casting quality. For gray iron casting trial, casting surface roughness of Badger is superior to Wedron and Unimin for the considered alloy and pouring settings. Similarly, casting surface roughness of Unimin sand systems are worse than the other two sand systems for the considered alloy and pouring conditions.

It is important to reiterate that conventional hot tensile strength test was incapable to detect differences between these three sand systems. If foundries are not able to detect difference between these types of changes which represents batch-to-batch variability in sand system’s raw materials, then they will not be able to link variation in casting quality to the changes in their process parameters.

CHAPTER V

CONTRIBUTIONS AND FUTURE WORK

Contributions

There are many contributions of this dissertation. For sharing knowledge regarding the research work conducted throughout the dissertation, three research papers have been published. Research work mentioned in chapter II of this document is published as “Using disc-shaped specimen tests to classify chemically bonded sand systems” in AFS transactions no. 18-035. SPC method related research work from chapter III is published as “PCA on TDT data to detect process shift in chemically bonded sand systems” in AFS transactions no. 19-127. Similarly, research work related to qualification of chemically bonded sand from chapter IV of this dissertation is published as “Qualification of chemically bonded sand systems using a casting trial for quantifying interfacial defects” in international journal of metalcasting, April 2018, Volume 12, Issue 2, pp-214-223. Furthermore, it is expected to publish one more paper in near future.

First contribution of this dissertation is that the disc-shaped specimen tests are able to accurately classify different sand systems in their respective classes. This demonstrates that the disc-shaped specimen tests are capable to differentiate small and large changes in chemically bonded sand systems. This was important to determine in order to develop an effective SPC method using data of these disc-shaped specimen tests that can help detect subtle changes in sand systems. These tests have been developed over more than twenty-five years of research effort at

WMU, but due to limited research, foundry societies were not influenced to use them for monitoring chemically bonded sand systems. This dissertation has proved that the disc-shaped specimen tests are capable to discriminate subtle changes in sand systems which has led these tests to be alternative standardized tests endorsed by American Foundry Society (AFS). In addition, many foundries around the world have started considering the disc-shaped specimen tests for the further research.

Second contribution of this dissertation is the SPC method using principal component analysis on the TDT data. This has open a new door for controlling chemically bonded sands in foundries. Until now, foundries were characterizing incoming sand system and checking individual properties such as mechanical, physical, and thermal properties of sand systems. The application of SPC using the TDT data provides an effective technique to monitor sand systems as the TDT incorporates coupled thermal, mechanical and physical properties of sand systems. This offers an opportunity to detect changes in the behavior of a sand system at elevated temperature and head pressure that can be adjusted to represent the actual casting scenario.

Third contribution of this dissertation is the quality control framework that combines the SPC method to casting quality. The quality control framework enables foundries to make right decision to improve casting quality and reduce overhead costs. This dissertation gives a new idea to sand binder suppliers to sell their products based on casting quality for a specific application. The casting trials used in the quality control framework provides an opportunity to take preventive measures before foundries experience heavy rejections. Sand binder supplier can develop database for different recipes of sand systems and its effect on casting quality for various casting applications. Furthermore, when foundries need an alternative molding media for economic, environmental and/or health related concerns, sand binder suppliers can qualify a newly developed chemically bonded sand system for a specific application and minimize the risk of deteriorating casting quality.

Future Work

The case study presented in quality control framework demonstrates that the application of the proposed SPC method and the quality control framework may help working foundries to quickly detect changes in a sand system which may affect the casting quality. Until now, the majority of the foundries remain hesitant to provide their foundry's quality data for the research, probably because of the guarantee/warranty concerns. However, it will be in interest of a foundry to implement this methodology to quickly detect a change in their sand systems and verify the effect of that change on casting quality. In this dissertation, all the disc-shaped specimens were made either at laboratory or at customer facility using a specialized tool that did not include process variation. For future work, it is recommended to implement the quality control framework in a working foundry where the disc-shaped specimens are being made along with the actual mold/core which will include production process variation for chemically bonded sand systems.

In this dissertation, only TDT is considered for the SPC as the SPC method using TDT data can detect changes due to variations in raw material of chemically bonded sand systems. However, when above mentioned process variation is included in specimens, a new SPC method may be needed to be efficient in detecting changes in sand systems. There are potential to perform other tests on the same specimen before and after TDT. As for example, first, ambient permeability can be performed on a disc-shaped specimen and then abrasion can be performed next as ambient permeability is nondestructive test. After performing abrasion test on the specimen, TDT can be performed on the other side of the disc-shaped specimen. In addition, TDT mass loss, retained strength test can also be performed on the same specimen after TDT. This will allow to find correlation between these test results. These test results can be included in multivariate analysis and another SPC method can be developed which can be more efficient than the one presented in this dissertation. Further study is recommended in this area.

In addition, newly developed casting trials for various defects such as erosion, distortion, gas porosity etc. that incorporate disc-shaped specimens can be included in quality control framework. Results of these type of casting trials can be integrated in solidification simulation software to predict the possible casting defect that may occur during the actual casting process for different types of sand systems. For this, boundary conditions in solidification simulation software must be created for several different types of chemically bonded sand system mold/core and further research is needed to accomplish the mentioned objective.

Furthermore, visualization of the behavior of disc-shaped specimen in TDT can be helpful to understand how the specimen is moving under the elevated temperature and pressure for a given test condition. Visualization software can be developed in which TDT data can be used to animate the behavior of disc-shaped specimen i.e. expansion, deformation, crack etc. to help engineer the chemically bonded sand systems to minimize the casting defects such as veining which is caused by a crack experienced by a sand mold/core. There might be a potential to relate the casting defects to the anomalies observed during TDT. Once the relation is found then casting trials can be eliminated and TDT alone can be able to qualify the chemically bonded sand system for a casting condition.

In today's world, the need of data analytics is continuously increasing in every aspect of life. Data analytic software can be developed that uses the developed SPC method which can perform complex calculations and provide green, yellow and red signal to foundry engineers who might not be an expert in the data analytics.

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