MEASUREMENT OF ELASTIC MODULUS OF PUNB BONDED SAND AS A FUNCTION OF TEMPERATURE

J. Thole and C. Beckermann
University of Iowa, Iowa City, IA, USA

Abstract

The stiffness of molds and cores has a large effect on casting quality in sand foundries. Measurements of the elastic modulus of PUNB bonded silica sand are performed from room temperature to 500C (932F). The measurements are taken almost instantaneously during the heating to capture the changes in the elastic modulus throughout the temperature range. The effect of the heating rate is investigated in detail. For an intermediate heating rate of 8C/min (14.4F/min), the elastic modulus decreases steeply from a room temperature value of about 3,900 MPa to 600 MPa at 125C (257F). Above 250C (482F), it increases to 1,200 MPa at 280C (536F) and then decreases again to 900 MPa at 325C (617F). Above 350C (662F), the elastic modulus increases almost linearly with temperature until it reaches 2,400 MPa at 500C (932F). At approximately 500C (932F), the strength of the bonded sand vanishes. At elevated temperatures, the elastic modulus is found to be a strong function of the heating rate and time. For example, while holding a specimen at a constant temperature of 200C (392F) for 30 min, the elastic modulus can increase from 600 MPa to 2,000 MPa. Only the steady-state values of the elastic modulus are in agreement with previous measurements. Upon cooling to room temperature, the bonded sand regains its full stiffness only for holding temperatures below about 275C (527F). These variations in the elastic modulus with temperature correlate well with the physical and chemical changes the binder undergoes during heating. Additional experiments are needed to investigate the elastic modulus variation for higher heating rates and other binder systems.

***Keywords**: mold properties, stiffness measurement, PUNB bonded sand, elastic modulus, casting simulation*

Introduction

The stiffness of the bonded sand used to make molds and cores has a large effect on the quality of castings produced in sand foundries. Weak molds and cores can result in excessive casting distortion or warpage. Many casting defects, such as hot tears and veins, are also strongly affected by the stiffness of the mold and cores. In this respect, it is important to not only know the stiffness of the bonded sand at room temperature, but also at the elevated temperatures encountered during and after solidification of a casting.

Casting simulation software has recently made some progress in the area of prediction of stresses, distortion and related defects. However, significant gaps exist in the knowledge of the mechanical properties of the metal and mold materials. Monroe *et al*.[1] found that the predicted stresses and distortions in steel casting are particularly sensitive to the elastic modulus (stiffness) of the sand mold. The objective of the present study is to accurately measure the elastic modulus of phenolic urethane no-bake (PUNB) bonded sand as a function of temperature, in order to provide improved input data for stress simulations.

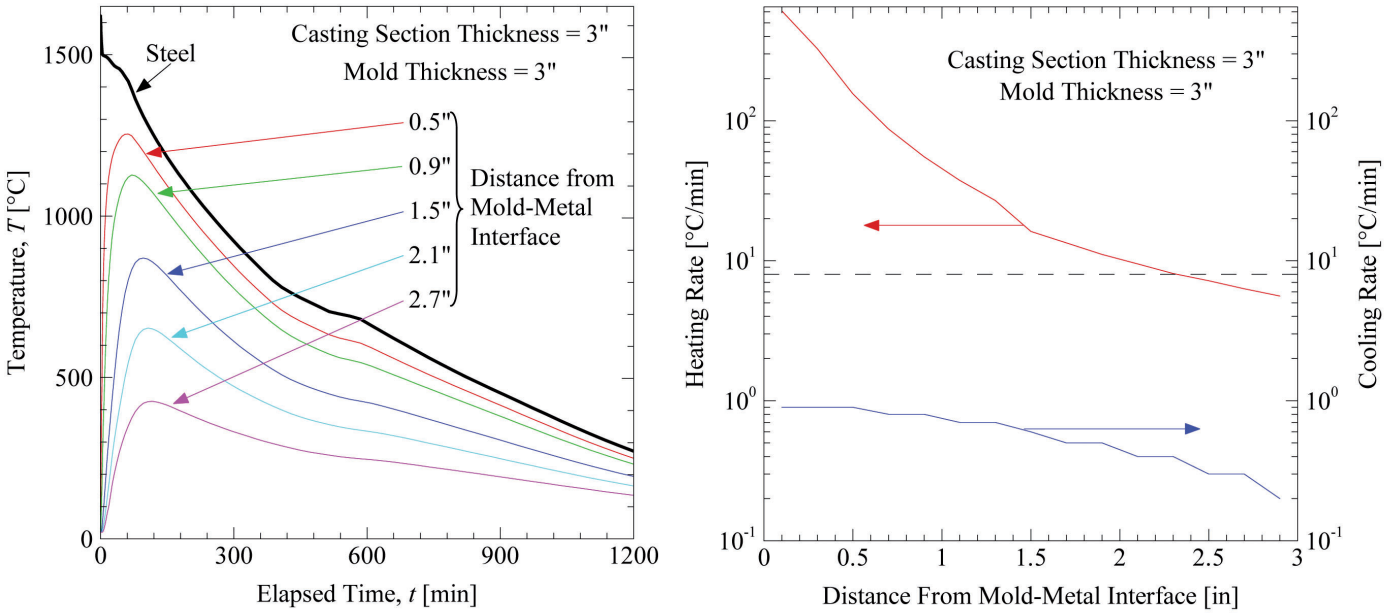
Measurements of the elastic modulus of chemically bonded sand first appeared in the late 1950's, where the effects of grip, shape and gauge length of tensile test specimens were investigated by Wallace and coworkers.[2] In a later study[3] employing a strain gauge, they verified that approximately the same value for the elastic modulus at room temperature is obtained when measured under compressive, tensile or bending loading. It was also found that for all loading methods, the bonded sand shows both elastic and brittle behavior.

More recently, the elastic modulus of phenolic urethane cold-box (PUCB) bonded sand was measured at elevated temperatures using a three-point bend apparatus.[4] It was found in this study that the elastic modulus decreases from about 4,300 MPa at room temperature to 2,200 MPa at 200C (392F). Above 200C (392F), the elastic modulus was observed to remain constant, except for a temporary re-stiffening to 3,000 MPa at 300C (572F). At 400C (752F), another increase to 3,000 MPa was measured. Very recently, Thiel[5] performed elevated temperature elastic modulus measurements of chemically bonded sand using a tensile testing machine with an extensometer and an elongated dog-bone test specimen. The results were in approximate agreement with those of Reference 4. In

both References 4 and 5, the bonded sand specimens were heated in an oven (in an inert atmosphere) to the desired test temperature, and the elastic modulus measurements were performed well after the specimens reached a uniform and constant temperature. The effect of heating rate was not investigated. In Reference 4, the measurements were performed inside of the oven, whereas in Reference 5 the specimens were removed from the oven before testing. In both references, the elastic modulus was measured at no more than ten discrete temperatures. Furthermore, the variation of the elastic modulus during cooling from an elevated temperature was not investigated.

In the present study, elastic modulus measurements are performed on PUNB bonded sand typical of steel casting molds. The experimental setup is similar to the one used in Reference 4 and uses a three-point bend apparatus.[6,7] The specimens are tested inside an oven in an inert atmosphere. Unlike in the previous studies, the present setup allows for elastic modulus measurements to be performed almost instantaneously. Hence, an almost continuous variation of the elastic modulus with temperature can be obtained. The effect of different heating rates is also investigated. In order to determine typical mold heating (and cooling) rates, a solidification simulation[8] was conducted of a large 7.62 cm (3 in) thick steel casting section with a 7.62 cm (3 in) thick mold. Predicted temperatures as a function of time are shown in Figure 1a, and the variations of the mold heating and cooling rates with distance from the mold-metal interface are plotted in Figure 1b. The heating/cooling rates represent averages over the time periods the temperatures in Figure 1a increase/decrease. It can be seen that within a distance of 2.54 cm (1 in) from the mold-metal interface, the temperatures in the mold reach values higher than 1,000C (1,832F) (Figure 1a) and the heating rates are above 50C/min (90F/min) (Figure 1b). Such high heating rates are difficult to achieve in an oven. In addition, a reasonably sized specimen would not be isothermal when heated at such high rates. However, at distances greater than 2.54 cm (1 in) from the mold-metal interface the heating rates are much lower, while the mold temperatures still reach values above 400C (752F). Between 3.81 cm (1.5 in) to 7.62 cm (3 in) from the mold-metal interface, the mold heating rates vary from about 20C/min (36F/min) to 5C/min (9F/min). Heating rates of that order of magnitude are utilized in the present measurements. Figure 1 also shows that after the initial heating, the mold cools down again. The cooling rates are much lower in magnitude than the heating rates. They decrease from about 1C/min (1.8F/min) to 0.2C/min (0.36F/min) with increasing distance from the mold-metal interface (Figure 1b). During the time period when the temperatures in the mold decrease, the mold can still have a strong effect on casting distortion.[1] Thus, the behavior of the elastic modulus during cooling, after heating to a certain temperature, is also investigated in the present study. In particular, it is of interest to understand if the elastic modulus takes on the same values during cooling as during heating and if the original room temperature value is recovered at the completion of cooling. Finally, the effects of the solvent and black iron oxide in the binder on the elastic modulus are investigated.

The specimen preparation and the experimental setup are described in the next section. The results of the present study are presented in Section 3, and the conclusions are summarized in Section 4.



(a) Predicted temperatures in the mold.

(b) Predicted average heating and cooling rates in the mold.

Figure 1. Predicted temperatures and average heating/cooling rates during casting of a three inch thick steel section surrounded by a three inch thick sand mold.

Experiments

The following sub-sections describe the preparation of the test specimens, the design of the experimental setup, and the experimental procedures. Then, a brief validation of the present tests is presented in which the elastic modulus of ASTM 304 stainless steel is measured at room and elevated temperatures. Finally, an error analysis is presented.

Specimen Preparation

The test specimens were prepared from silica lake sand, with a grain fineness number of 55 (IC55), and a phenolic urethane no-bake (PUNB) binder system with black iron oxide (BIO). All sand and binder system characteristics are summarized in Table 1. As shown in Figure 2, a nine screen test was run to obtain the grain fineness number and measure the size distribution of the sand grains. The values for the binder percentage (1.25% of total weight), binder ratio (60:40), catalyst percentage (8% of binder weight) and additives (BIO, 3% of total weight) were obtained by polling seven steel foundries and taking the average of their responses. The porosity of each specimen was measured using a standard immersion test. The mean porosity of all specimens was 32.8%. Note from Table 1 that the measured porosities fall within a narrow band of ±0.9%.

The specimens were prepared by first mixing the black iron oxide into the sand using a kitchen-aid mixer to ensure a uniform distribution. Then, the binder was added according to a procedure recommended by the binder manufacturer. Part 1 and the catalyst were added to the sand, mixed for 45 seconds, and then tossed to bring the sand from the bottom to the top. The batch was mixed for another 45 seconds and tossed again. After the second toss, part 2 was added to the batch and mixed for another 45 seconds, which was followed by a third and final toss. The batch was mixed for a final 45 seconds before depositing it into the dump box. The sand-binder mixture was then rammed by hand into the pattern, while striving to achieve a uniform density, and allowed to set in the pattern before stripping. The specimens were stripped when the compacted sand withstood 20 psi of compressive stress without visible deformation.[9] The dump box was capable of making six specimens with a 25.4 mm (1 in) square cross-section and

Table 1. Characteristics of the PUNB Bonded Sand Specimens Used in the Elastic Modulus Measurements

Sand Type	IC55 round grain silica lake sand
Binder	Pepset x1000, x2000
Catalyst	Pepset 3500
Binder Percentage	1.25% by total weight
Binder Ratio	60:40
Catalyst Percentage	8% of binder weight
Additives	3% black iron oxide by total weight
Specimen Porosity, $\bar{\phi} \pm 1\sigma$ [%]	32.8 ± 0.9

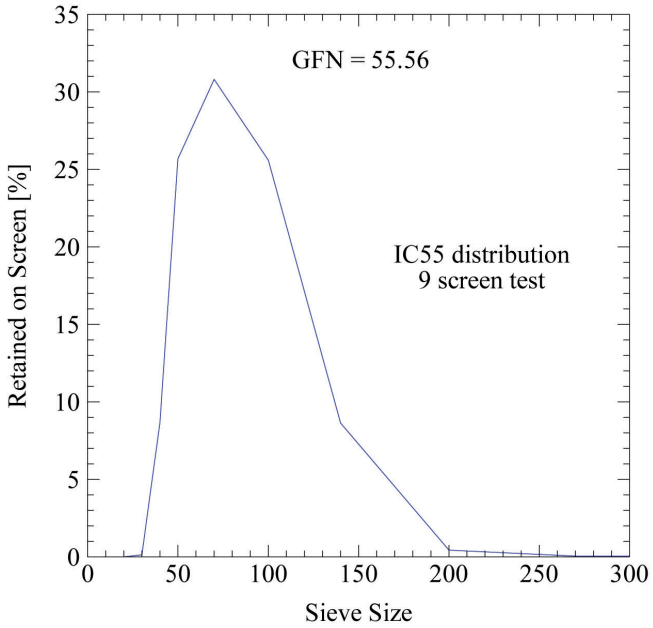


Figure 2. Nine screen sieve test performed on a 50 gram sample of IC55 silica lake sand.

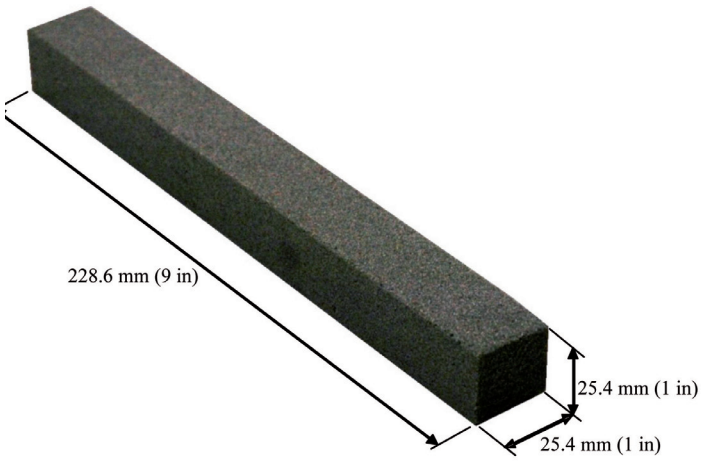


Figure 3. Photograph of a three-point bend specimen containing 1.25% binder by total weight at a 60:40 ratio of part 1 to part 2, and 3% black iron oxide.

a 228.8 mm (9 in) length. The specimens were allowed to cure for at least 24 hours before testing. A photograph of a test specimen is shown in Figure 3.

Experimental Setup and Procedures

A schematic of the three-point bend apparatus is shown in Figure 4. The three-point bend apparatus was placed inside a model OH-O1O-F1_CO-12-12-18 Thermcraft oven capable of reaching 538C (1,000F). The oven was purged of oxygen using nitrogen from a tank at a flow rate of 1 m^3/hr (35 ft^3/hr). The temperature of the oven was controlled using a 2216 Eurotherm model 1D1-16-230 control system. This system controls the temperature using a 230V, 3000W heating coil at 14.6 Amps. A cooling system, consisting of copper tubing through which cold water was circulated, was added to the oven to cool the system after a test at elevated temperature. The use of a separate cooling system allows the specimen to cool in an oxygen-free environment over a range of cooling rates.

The three-point bend test fixture was designed to follow ASTM Standard D5934[7], a method for measuring the elastic modulus of thermoplastics and thermosetting plastics. The support and loading heads were made from 12.54 mm (0.5 in) diameter cylindrical steel bars. The bars provide enough surface area to prevent any indentation caused by the loading or support heads. The support heads were welded to a base plate to ensure a constant support span of 190.56 mm (7.5 in). This distance between the supports results in an overhang of the specimens that is sufficient to avoid slipping. The loading head was aligned using a guide that was welded to the base plate. The guide ensures consistent placement of the loading head in order to reduce variability in the elastic modulus measurements.

Specimen deflection was measured using two Omega LD610-5 linear variable differential transformers (LVDTs). The LVDTs were located outside the oven by suspending them from a ladder stand. Quartz rods were used to extend the LVDT probes into the oven through a port hole located above the fixture. The port hole was insulated with fiberglass to protect the LVDTs from the oven when operated at high temperatures. One probe was situated on a table that straddles the specimen and rests on the support heads. This LVDT measured the displacement of the support heads. The loading head probe passed through a hole in the table and a tube that was welded to a small plate which, in turn, was placed on the loading head. This prevents the loading head probe from "walking" off the loading head and rendering the test invalid.

The specimen was loaded using a cantilever system located beneath the oven. The loading head was connected to the cantilever system using a series of mechanical connections exiting the oven through a port hole located directly beneath the test fixture. Between the port hole and the cantilever system, a load cell (Omega LC703-50) was installed to measure the applied force. The cantilever system consisted of a wooden board that was connected by a hinge to the table on which the oven rested. A hanging mass at the opposite end of the hinge provided the loading force for the system. The load was controlled with an eye and hook turnbuckle that supported the cantilever. Using a simple wrench, the load could be increased and decreased in a rapid fashion.

Two Type K thermocouples were used to measure the surface and center temperature of a separate "dummy" specimen located at the same elevation in the oven as the test specimen. A dummy specimen was used in order to keep the test specimen free of any modifications.

All devices were powered using an Elenco Precision Deluxe model XP-620 regulated power supply. The data was collected using a 16-bit IOtech 3005 Personal DAQ system connected to a laptop via USB. The software DasyLab was used to control the data acquisition system. A sampling frequency of 10 Hz, with an over-sampling rate of 8192, was used for all measurements. With these settings, each analog channel is sampled for 8,192 µs and a 16-bit average value over the scan period is returned.

The specimen deflection, D, was obtained by taking the difference between the displacements measured by the loading head and support head displacement LVDTs. The

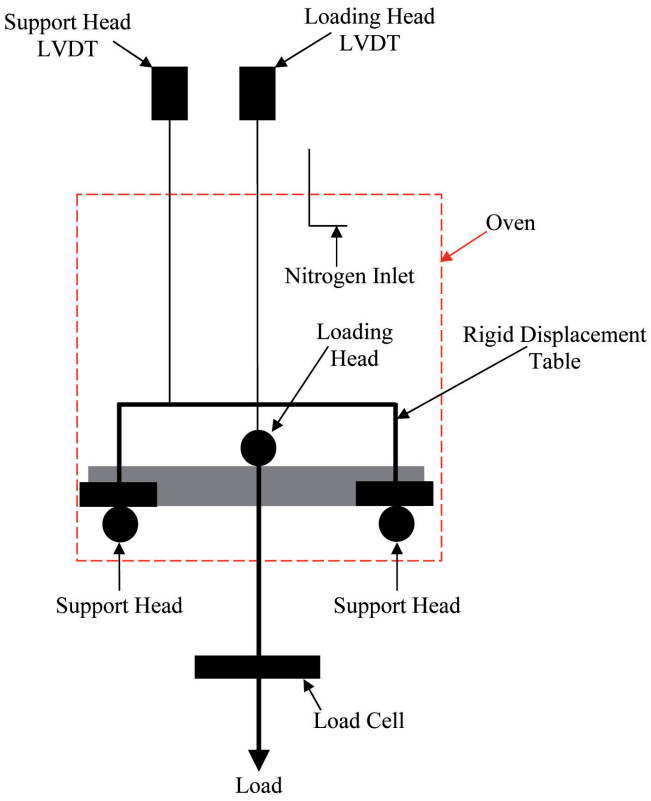


Figure 4. Schematic of three-point bend experimental setup.

load cell was carefully calibrated to measure the loading force, F. With this data, the stress σ, strain ε, and elastic modulus E, were calculated from the following three-point bend equations[7]:

$$\sigma = \frac{3FL}{2bd^2} \qquad \text{Equation 1}$$

and

$$\varepsilon = \frac{6Dd}{L^2} \qquad \text{Equation 2}$$

thus

$$E = \frac{\sigma}{\varepsilon} = \frac{L^3}{4bd^3}\left(\frac{F}{D}\right) \qquad \text{Equation 3}$$

where L is the support span, b is the specimen width as viewed by the loading head, and d is the specimen depth as viewed by the loading head.

In a typical test, a specimen was placed into the three-point bend apparatus and several measurements of the elastic modulus were first performed at room temperature. The load was kept well below that necessary to break the specimen. Then, the oven was turned on and the oven control system was set such that the temperature of the specimen increased at an approximately constant rate. The heating rate is one of the experimental variables in the present study. Approximately once every minute during heating (for a heating rate of 8C/min [14.4F/min]), the specimen was loaded and unloaded in order to measure the elastic modulus as a function of temperature. Again, the maximum load was kept to a sufficiently low level that the specimen did not break. A certain minimum load was maintained in order to ensure good contact between the specimen and the loading head. A test concluded when the specimen reached a temperature of approximately 500C (932F). At that temperature, the strength of the bonded sand vanishes because most of the binder has decomposed. Up to 80 elastic modulus measurements were performed in each test.

Validation

In order to validate the present experimental setup and measurement procedures, at both room temperature and elevated temperatures, tests were performed using a material with a well-known elastic modulus. The material chosen was ASTM 304 stainless steel. Figure 5 compares the present elastic modulus measurements with the measurements of Sakumoto *et al.*[10] Good agreement can be observed at both room temperature and 400C (752F).

Error Analysis

A simple root-sum-squares (RSS) error analysis was performed to estimate the error in the present elastic modulus measurements. Table 2 shows the sources of error in the individual measurements for a room temperature example. For the specimen deflection and the loading force, only the largest measured values (in the elastic regime) are listed. Table 3 shows the resulting ranges and errors in the elastic modulus. It can be seen that the measurement of the specimen deflection is the single largest source of error. The specimen width measurement is also a relatively large source of error, which can be attributed to the roughness of the top surface of the bonded sand specimens. Overall, the error in the present room temperature elastic modulus measurement is estimated to be ±1.5%. A similar accuracy can be expected at elevated temperatures.

Results

Stress-Strain Curves

In order to obtain a few complete stress-strain curves, preliminary experiments were conducted in which the load was increased until the specimens broke. The specimens were heated from room temperature to the desired test temperature at a rate of 8C/min (14.4F/min). Once the specimens reached the test temperature, the load was increased immediately without any further change in the temperature. Representative stress-strain curves at four different test temperatures are provided in Figure 6. A straight line was fit to the elastic portion of the stress-strain curves, with the slope representing the measured elastic modulus.

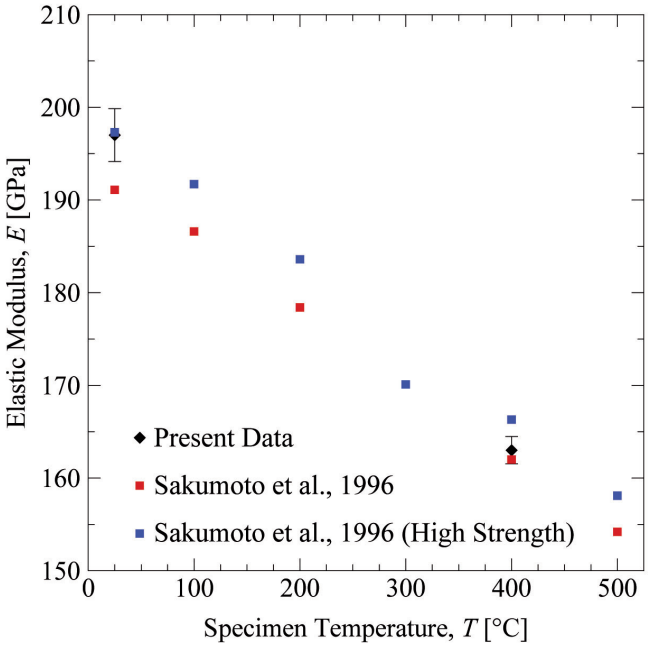


Figure 5. Comparison of present measurements of the elastic modulus of ASTM 304 stainless steel as a function of temperature with data from Sakumoto et al.[10]

Figure 6 shows that at 25C (77F), 350C (662F) and 450C (842F) the bonded sand behaves in a predominantly elastic manner, with failure occurring in a brittle mode. However, at 180C (356F), and to some extent at 350C (662F), large plastic deformations can be observed before the specimen breaks. While the elastic behavior can be expected to be the same under any loading condition,[3] the inelastic part of the stress-strain curves is specific to the present three-point bend test. Figure 6 also indicates that the elastic modulus and the ultimate strength and strain (at breaking) vary with temperature in a complex manner. The elastic modulus and strength decrease rapidly with increasing temperature from room temperature to 180C (356F). Then, the elastic modulus and strength increase again with temperature, while the ultimate strain decreases. Between 350C (662F) and 450C (842F), the elastic modulus increases, but the ultimate strength and strain decrease.

These non-monotonic variations of the mechanical properties with temperature, and the presence of inelastic behavior, are a new finding of the present study. As is shown in the following sub-sections for the elastic modulus, they are a direct result of the effect of the heating rate and the amount of time a specimen is held at a given temperature. In all previous studies,[4,5] the specimens were held at an elevated temperature for a long time, such that "steady-state" values of the mechanical properties were obtained and the heating rate played no role. In those studies, the mechanical properties were generally found to be monotonically decreasing with increasing temperature. In the present experiments, the specimens are heated at rates that are, to some extent, representative of the heating rates encountered in actual castings (see Introduction), and the measurements are performed instantaneously once the desired temperature is reached. This causes the difference in the observed behavior. Here, it should be kept in mind that the ultimate strength and strain values that can be read from Figure 6 are specific to the present three-point bend test and would be different under pure tension or compression. However, the value of the elastic modulus is independent of the loading method.[3] This is the reason why the present study focuses solely on the elastic modulus.

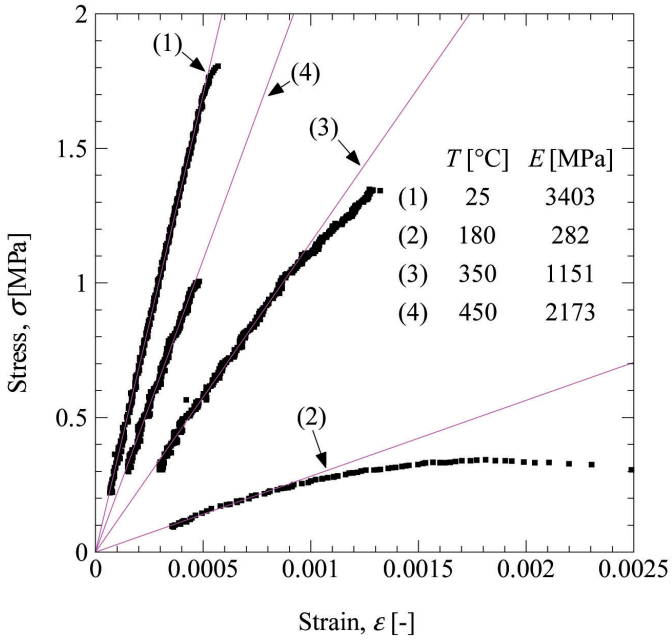


Figure 6. Typical stress-strain curves at four different temperatures. The specimens were heated at a rate of 8°C/min and loaded at the desired test temperature until breaking. The straight lines represent best fits to the data in the elastic regime.

Table 2. Sources of Error in an Elastic Modulus Measurement at Room Temperature

Source of Error	Measured Value	± error
Span Length, *L* [mm]	190.56	± 0.01
Specimen Width, *b* [mm]	26.03	± 0.23
Specimen Thickness, *d* [mm]	25.50	± 0.02
Specimen Deflection, *D* [mm]	0.0766	± 0.0009
Applied Loading Force, *F* [N]	67.275	± 0.006

Table 3. Errors in the Elastic Modulus for a Room Temperature Test

	Elastic Modulus [MPa]		
Source of Error	R+	R-	±dR
Span Length, *L* [mm]	3521	3520	± 0.5
Specimen Width, *b* [mm]	3490	3552	± 31.0
Specimen Thickness, *d* [mm]	3512	3529	± 8.5
Specimen Deflection, *D* [mm]	3480	3562	± 41.0
Applied Loading Force, *F* [N]	3521	3520	± 0.5
Reported Elastic Modulus, *E* [MPa]	3520		± 52.1 ± (1.5%)

Figure 7 shows an example of a stress-strain curve that was obtained during a typical test, where a specimen was loaded and unloaded during heating without breaking it. Each loading cycle corresponds to a different temperature between room temperature and 500C (932F). At some temperatures, a small amount of inelastic deformation could not be avoided. The total inelastic strain at the conclusion of the test is less than 0.5%. As demonstrated in Figure 6, only the straight portions of the stress-strain curve, during loading, are used to determine the elastic moduli.

Elastic Modulus Variation at an 8°C/min (14.4°F/min) Heating Rate

Numerous tests were performed for an average heating rate of 8C/min (14.4F/min). As indicated in Figure 1b by a dashed line, this heating rate is typical for locations in the mold that are between 2.54 cm (1 in) and 7.62 cm (3 in) away from the mold-metal interface (for a steel casting). Figure 8 shows the elastic modulus measurements, as well as the measured temperatures, as a function of time for a typical test. The center and surface temperatures are always within 10C (18F) of each other. This temperature non-uniformity of the specimen was still deemed acceptable. The lack of temperature uniformity prevents experiments from being conducted at much higher heating rates. At lower heating rates, the specimens were generally more isothermal. As can be seen from the slope of the temperature curves, the heating rate is not completely constant. The variation in the heating rate was always less than ±1.5C/min (2.7F/min), which again was deemed acceptable. The approximately 80 elastic modulus measurements in Figure 8 provide an almost continuous variation of the elastic modulus with time.

Figure 9 shows the elastic modulus measurements for six different specimens that were all heated at a rate of 8±1.4C/min (14.4±2.52F/min). Here, the elastic modulus is plotted directly against the measured temperature. Three of the specimens contained black iron oxide and three did not. It can be seen that there is no discernable difference in the elastic modulus between the two types of specimens. This indicates that the addition of black iron oxide has no effect on the elastic modulus. All data fall within a relatively narrow band and were fit to a line using a 13-point moving average. This line is also shown in Figure 9. In addition, Figure 9 shows the average of all room temperature elastic modulus measurements for the six specimens. This average is equal to 3,920 MPa, with a standard deviation of 343 MPa. This relatively large standard deviation is not due to measurement uncertainty (see Table 3). It is a result of unavoidable variations in the preparation of the specimens.

The variation of the elastic modulus with temperature can be best described by following the line in Figure 9. The elastic modulus decreases steeply with increasing temperature from the room temperature value of 3,920 MPa to about 600 MPa at 125C (257F). Note the small knee in the line at about 65C (149F). Between 125C (257F) and 250C (482F), the elastic modulus is relatively constant. Above 250C (482F), it increases to 1,200 MPa at 280C (536F) and then decreases again to 900 MPa at 325C (617F). Above 350C (662F), the elastic modulus increases almost linearly with temperature until it reaches 2,400 MPa at 500C (932F). At approximately 500C (932F), the strength of the bonded sand vanishes and the specimens collapse under the weight of the loading head.

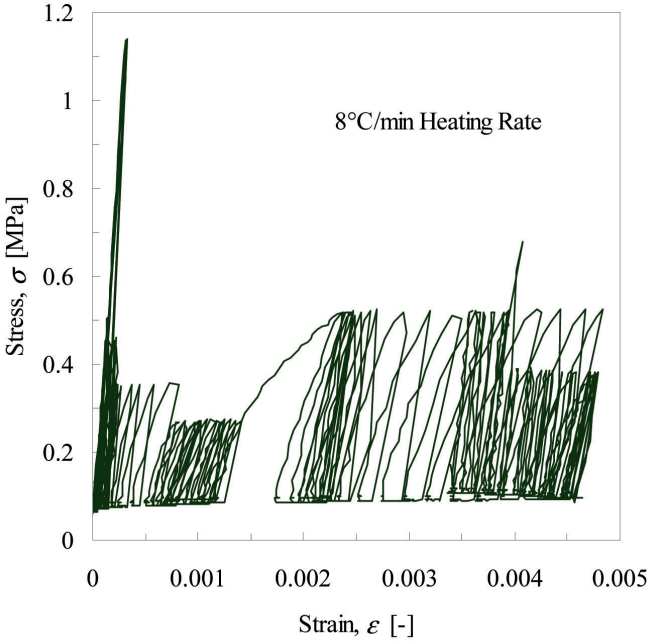


Figure 7. Typical stress-strain curve for a single specimen under repeated loading and unloading during heating at an average rate of 8°C/min.

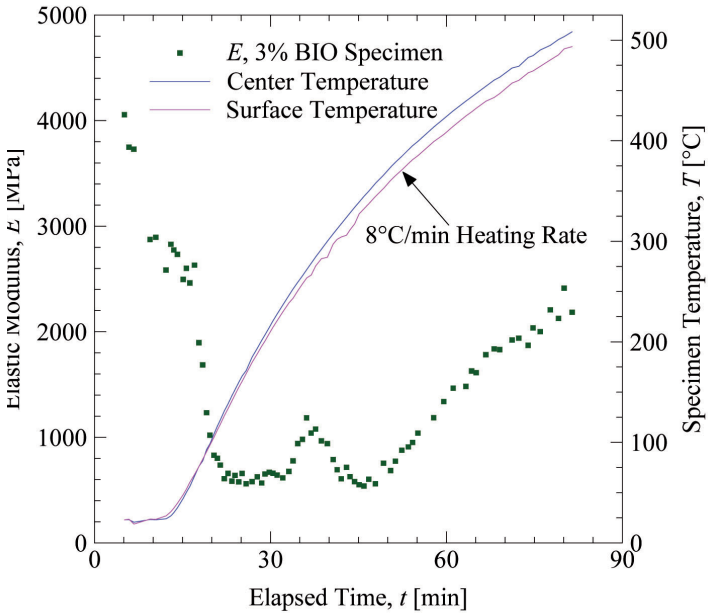


Figure 8. Measured elastic modulus and temperatures as a function of time for a typical test with an average heating rate of 8°C/min.

The above variations correlate well with the chemical reactions the binder undergoes during heating. Giese *et al.*[11] measured the energy released during heating (at a 10C/min (18F/min) rate) of a 60:40 PUNB sample using differential scanning calorimetry (DSC). The various peaks in the DSC curve were associated with specific changes in the binder composition. Figure 10 shows the findings of Giese *et al.* superimposed on the fit of the elastic modulus data from Figure 9. It can be seen that the start of solvent vaporization corresponds to the small knee in the elastic modulus curve at about 65C (149F). The end of solvent vaporization coincides with the elastic modulus reaching the 600 MPa value at about 125C (257F). The start of urethane bond breakage at 180C (356F) can be associated with a small kink in the elastic modulus curve. The peak in the elastic modulus around 280C (536F) coincides with the maximum decomposition rate and the end of urethane bond breakage. The linear increase in the elastic modulus above 350C (662F) can be associated with the breakdown of the binder to polymer aromatics.

Effect of Solvent

The results shown in Figure 10 indicate that the solvent in the binder may have an effect on the elastic modulus. Therefore, additional tests were performed where the solvent was removed from the specimens prior to testing by heating the specimens to 140C (284F) and allowing them to cool down to room temperature again. The results of two such tests (at a 8C/min (14.4F/min) heating rate) are shown in Figure 11 and compared to the fit of the elastic modulus data from Figure 11 (without solvent removal). Despite the scatter in the data, it can be seen that the solvent has an effect on the elastic modulus at temperatures below about 150C (302F). While the room temperature elastic modulus is approximately the same with and without solvent, the elastic modulus between 50C (122F) and 150C (302F) is generally higher with the solvent removed. The differences can be as large as a factor of two. However, at temperatures above 150C (302F), Figure 11 shows that the elastic modulus of the specimens with the solvent removed follows the same variation with temperature as the fit of the elastic modulus data from the six original specimens where the solvent was not removed.

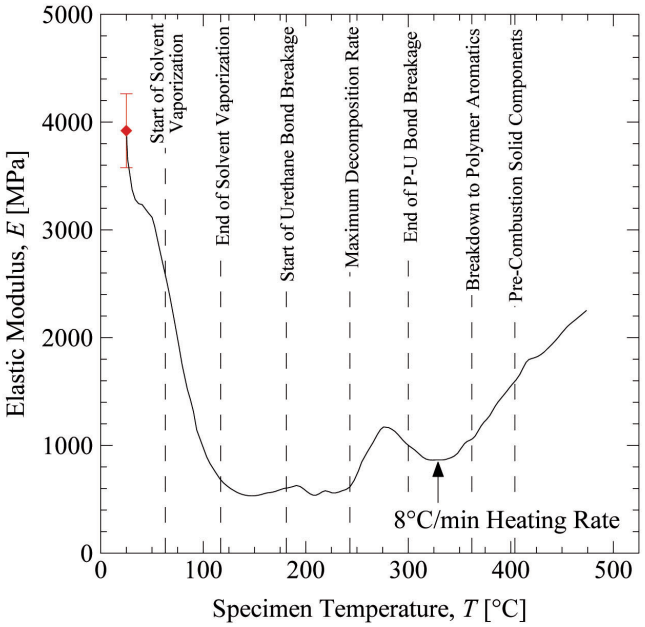


Figure 10. Comparison of the measured elastic modulus variation with the DSC data from Giese et al.[11] for a 60:40 ratio PUNB sample heated at 10°C/min.

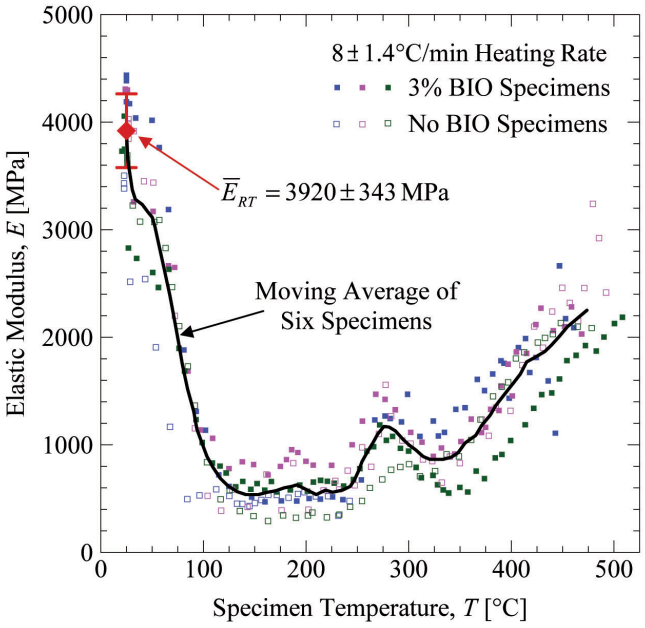


Figure 9. Measured elastic modulus as a function of temperature for an average heating rate of 8°C/min.

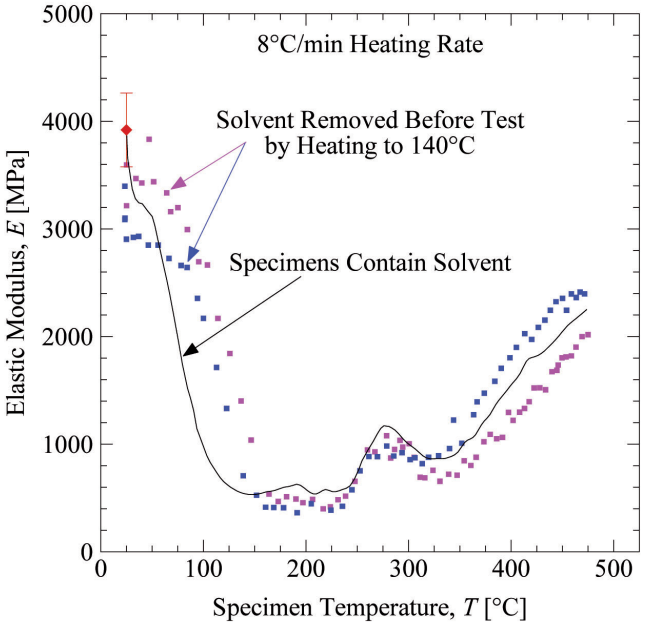


Figure 11. Comparison of the elastic modulus variation with temperature for specimens with and without the solvent removed.

Effect of Heating Rate on the Elastic Modulus Variation

In order to investigate the effect of heating rate, additional tests were performed at heating rates of 5C/min (9F/min), 2C/min (3.6F/min), and 0.8C/min (1.44F/min). In view of Figure 1b, such low heating rates occur in steel casting molds only far from the mold-metal interface. The results of these elastic modulus measurements are shown in Figure 12 and compared to the fit of the elastic modulus data from Figure 9 for a heating rate of 8C/min (14.4F/min). It can be seen that the heating rate has a strong effect on the elastic modulus variation with temperature. Within the present range, the elastic modulus at a given temperature can vary by more than a factor of two depending on the heating rate. With decreasing heating rate, the minimum in the elastic modulus at 125C (257F) shifts to higher values. For the lower three heating rates, and above 175C to 200C (347F to 392F), the elastic modulus increases almost linearly to some maximum value. The maximum value is reached at a temperature between 375C to 425C (707F to 797F) and is equal to about 2,800 MPa. Beyond that temperature, the elastic modulus decreases steeply and the specimens lose their strength.

Although DSC data is not available for the lower heating rates, the large differences in the elastic modulus variations observed in Figure 12 are clearly linked to the dependence of the chemical changes of the binder on the heating rate. In particular, the urethane bond breakage appears to be a very time dependent process. For the lower heating rates, there is enough time for the urethane bond breakage to complete at lower temperatures. Once the urethane bonds are broken, the breakdown to polymer aromatics can commence, which in turn coincides with the linear increase in the elastic modulus with temperature. The breakdown to polymer aromatics does not appear to be a time dependent process, since the slopes of the linear increase in the elastic modulus with temperature are approximately the same for all heating rates. However, the temperature at which all bonds are broken shifts to lower values with decreasing heating rate.

Also shown in Figure 12 is a curve labeled "steady-state". This curve will be discussed in greater detail in the next sub-section, but it can be thought of as corresponding to an "infinitely" slow heating rate. It can be observed in Figure 12 that with decreasing heating rate, the elastic modulus curves approach this steady-state curve.

Elastic Modulus During Holding at Elevated Temperatures

The strong dependence of the elastic modulus on the heating rate observed in Figure 12 raises the question what the elastic modulus variation is for an infinitely slow heating rate. For example, does the elastic modulus at about 150C (302F) continue to increase with decreasing heating rate? In order to investigate this issue, a special set of experiments was conducted where a specimen was heated (at approximately 8C/min (14.4F/min)) to a pre-selected "hold" temperature and then held at this temperature for a time sufficient for the elastic modulus to attain a constant "steady-state" value. Representative results are shown in Figure 13 for four different hold temperatures: (a) 50C (122F), (b) 200C (392F), (c) 300C (572F), and (d) 370C (698F). In each of the graphs, the measured elastic modulus and temperature are plotted as a function of time. It can be seen that during the heating period, the elastic modulus varies in a similar fashion as already discussed in connection with Figure 8. However, during holding of the specimen at a given temperature, the elastic modulus can be seen to continue to change with time, except for the experiment with the lowest holding temperature (50C (122F), Figure 13a). For the higher three hold temperatures, the elastic modulus always increases during the holding period, until a constant steady-state value is achieved.

The constant steady-state values for the elastic modulus measured in the present set of experiments are plotted as a function of the hold temperature in Figure 14. It can be seen that the steady-state values for the elastic modulus for hold temperatures below 100C (212F) are close to the instantaneous values measured in the continuous heating experiments. This indicates that below 100C (212F), the heating rate does not have an influence on the elastic modulus (see Figure 12). For hold temperatures between 100C (212F) and 200C (392F), the steady-state elastic modulus is equal to about 2,000 MPa. Then, the elastic modulus increases to about 3,000 MPa at 270C (518F) and drops to 2,400 MPa at 300C (572F). Be-

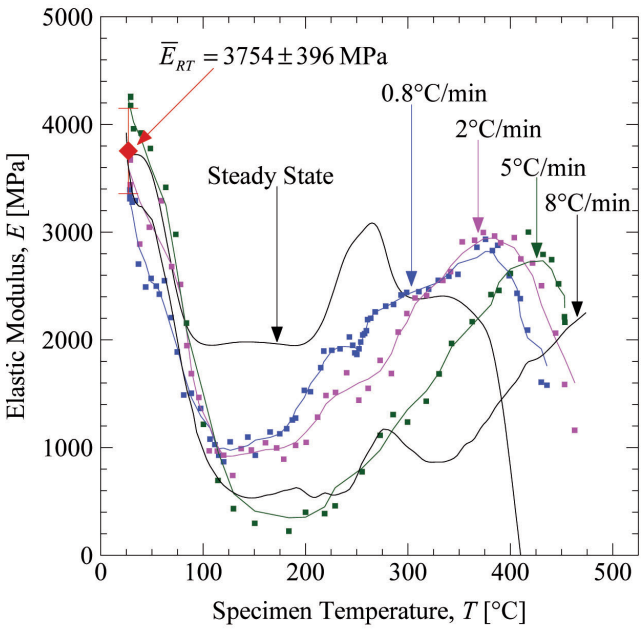


Figure 12. Comparison of the elastic modulus variation with temperature for specimens heated at 0.8, 2, 5, and 8°C/min with a fit line along with the steady state data.

tween 375C (707F) and 410C (770F), the elastic modulus drops to zero. As can be seen in Figure 12, the steady-state elastic modulus values between 100C (212F) and 200C (392F) are much higher than those for finite heating rates. Also, the complete loss of stiffness occurs at a lower temperature when the specimen is heated "infinitely" slowly.

The steady-state elastic moduli measured in the present set of experiments are in close agreement with those measured in Reference [4]. This can be expected because the specimens in the experiments of Reference [4] were indeed held at elevated temperatures for some time before the elastic modulus measurement was performed. The agreement instills considerable confidence in the present measurements.

Retained Room Temperature Elastic Modulus

After the elastic modulus specimens were held at an elevated temperature for a long period of time, the power to the oven was shut off and the cooling system was activated. The oven was allowed to cool until the specimens were back at room temperature. Then, several measurements of the retained room temperature elastic modulus were performed for each specimen. The results of these measurements are plotted as a function of the elevated hold temperature prior to cooling in Figure 15.

Figure 15 shows that for hold temperatures up to about 275C (527F) the specimens fully recover their initial room temperature stiffness upon cooling. There appears to be a

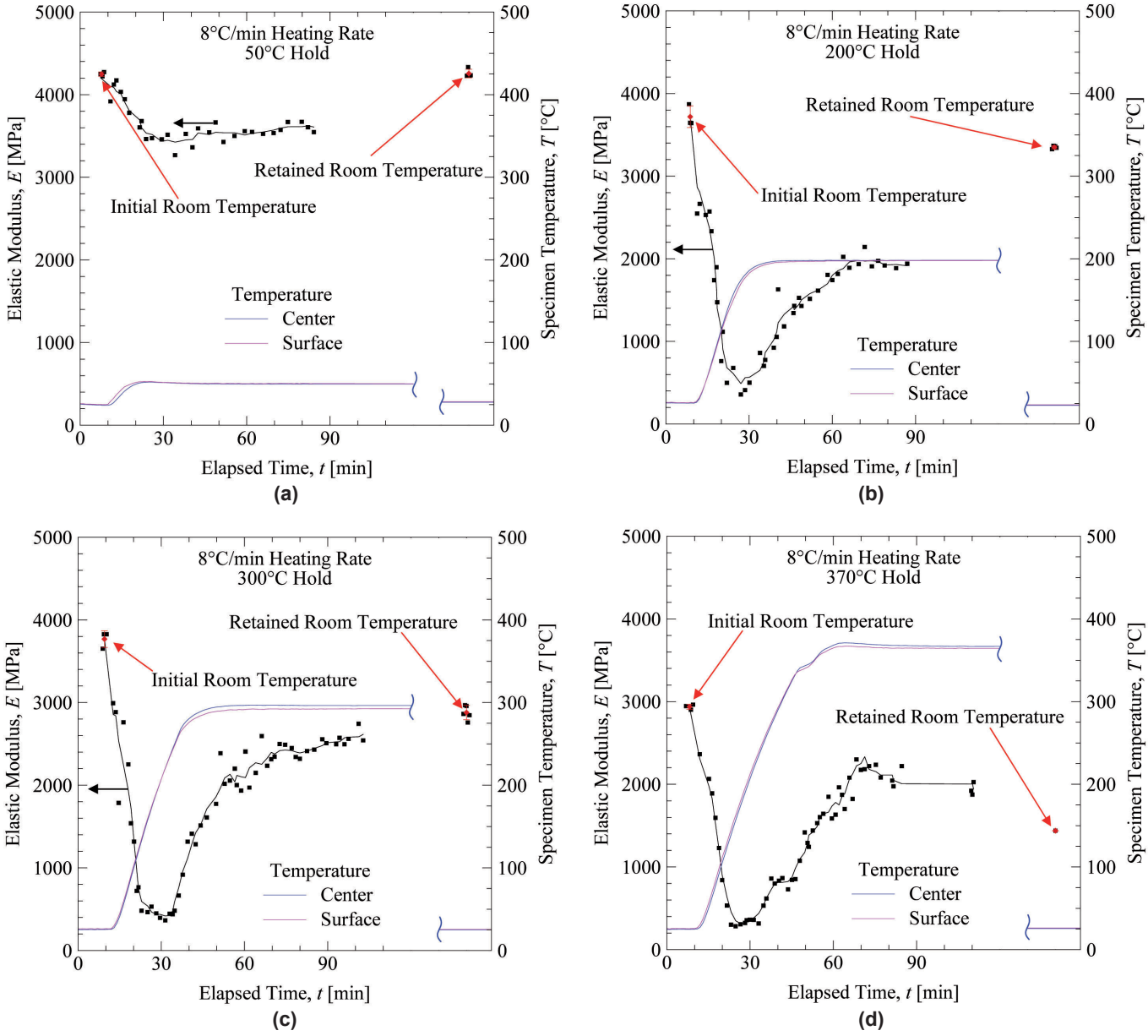


Figure 13. Elastic modulus variation during heating and holding at an elevated temperature until a constant steady-state value is attained. The holding temperatures are (a) 50°C, (b) 200°C, (c) 300°C, and (d) 370°C. The figures also show the measured retained elastic modulus after cooling to room temperature.

slight dip in the retained room temperature elastic modulus at 150C (302F), but it is within the standard deviation of the measurements. This indicates that the urethane bond breakage, which occurs up to about 300C (572F) (Figure 10), is fully reversible upon cooling. However, for hold temperatures above 275C (527F) the retained room temperature elastic modulus declines first gradually up to about 350C (662F), and then steeply to zero at about 400C (752F). This degradation in the stiffness can be expected because above about 350C (662F) the binder starts to break down to polymer aromatics (Figure 10), which is an irreversible chemical reaction. Figure 15 clearly shows that bonded sand heated for a prolonged period of time at temperatures above 400C (752F) does not regain any stiffness upon cooling.

Conclusions

The present three-point bend elastic modulus measurements for PUNB bonded sand reveal a complex behavior during heating and cooling. Previous studies have only reported the steady-state elastic moduli after extended holding of the bonded sand at elevated temperatures. The present measurements indicate that, for temperatures above 100C (212F), the variation of the elastic modulus with temperature is a strong function of the heating rate and, hence, time. Upon cooling from temperatures above about 275C (527F), the permanent degradation of the binder prevents the bonded sand from regaining its original stiffness.

Before the present data can be used in stress simulations of a casting process, additional experiments are needed for higher heating rates. Within 2.54 cm (1 in) of the mold-metal interface, the heating rates are greater than 50C/min (90F/min) (for a steel casting). Once elastic modulus measurements at higher heating rates are available, all data need to be correlated as a function of both temperature and heating rate. Furthermore, the variation during cooling deserves greater attention. In order to create a complete model for the elastic modulus of bonded sand, it appears necessary to develop a quantitative description of the temperature and time dependent chemical changes the binder undergoes during heating and cooling. Then, the elastic modulus could be correlated directly with the chemical state of the binder, rather than with temperature and rates of temperature change. Additional study of the effect of different binder compositions on the elastic modulus would also be of great value.

Acknowledgements

This article is based upon work supported by the U.S. Department of Energy under Award No. DE-FC36-04GO14230. The authors would like to thank the Steel Founders' Society of America for their support of this work. The authors would also like to express their gratitude to Mr. Jerry Thiel and staff of the University of Northern Iowa for their help with making the dump box and test specimens, and to Prof. Colby Swan of the University of Iowa for the use of lab equipment.

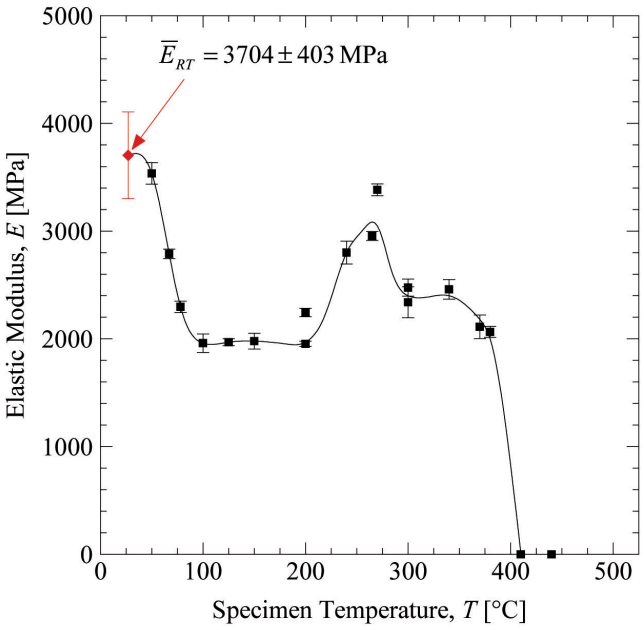


Figure 14. Steady-state elastic modulus as a function of the hold temperature.

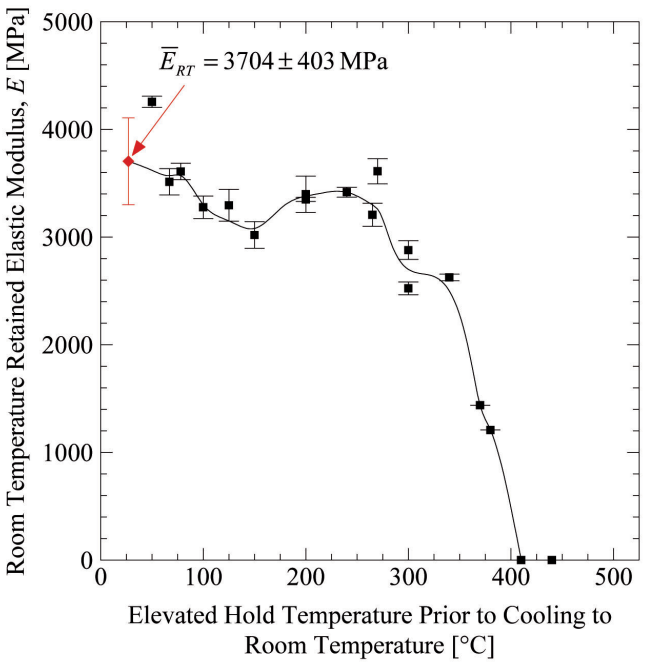


Figure 15. Retained room temperature elastic modulus as a function of the hold temperature prior to cooling.

REFERENCES

1. Monroe, C.A., Beckermann, C., and Klinkhammer, J., "Simulation of Deformation and Hot Tear Formation Using a Visco-Plastic Model with Damage," in Modeling of Casting, Welding, and Advanced Solidification Processes - XII, eds. S.L. Cockcroft and D.M. Maijer, TMS, Warrendale, PA, 2009, pp. 313-320.
2. Ahearn, P.J., Quigley, F., Bluhm, J.I., and Wallace J.F.,, "Some Considerations On The Tensile And Transverse Strength Testing Of Shell Mold And Core Sands," *AFS Transactions*, vol. 64, pp. 125-132 (1956).
3. Quigley, F., Ahearn, P.J., and Wallace J.F., "Influence Of Various Bonding Materials On Stress-Strain Characteristics Of Bonded Sands," *AFS Transactions*, vol. 65, pp. 319-322 (1957).
4. "Final Report," Arbeitsgemeinschaft Industrieller Forschungsvereinigungen Otto von Guericke, e.V. (AiF), (2008).
5. Thiel, J., "High Temperature Physical Properties of Chemically Bonded Sands Provide Insight into Core Distortion," Proc. 62nd SFSA Technical and Operating Conference, Chicago, Illinois, December 2008.
6. ASTM Standard C1211, 2002 (2008), "Standard Test Method for Flexural Strength of Advanced Ceramics at Elevated Temperatures," ASTM International, West Conshohocken, PA, 2008, DOI: 10.1520/C1211-02R08.
7. ASTM Standard D5934, 2002 "Standard Test Method for Determination of Modulus of Elasticity for Rigid and Semi-Rigid Plastic Specimens by Controlled Rate of Loading Using Three-Point Bending," ASTM International, West Conshohocken, PA, 2002, DOI: 10.1520/D5934-02.
8. MAGMASOFT® v4.6, MAGMA GmbH, Kackertstrasse 11, 52072 Aachen, Germany.
9. Naro, R.L. and Hart, J.F., "Phenolic Urethane No-Bake Binders: Ten Years of Progress," *AFS Transactions*, vol. 88, pp. 57-66 (1980).
10. Sakumoto, Y., Nakazato, T., and Matsuzaki, A., "High-Temperature Properties of Stainless Steel for Building Structures," *Journal of Structural Engineering*, vol. 122, n 4, pp. 399-406, (April 1996).
11. Giese, S.R.., Roorda, S.C., and Patterson, M.A., "Thermal Analysis of Phenolic Urethane Binder and Correlated Properties," *AFS Transactions*, vol. 117, pp. 355-366 (2009).