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Comparing Refractory Coatings on Shell Sand Utilizing Elevated Temperature and Collapsibility Testing

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COMPARING REFRACTORY COATINGS ON SHELL SAND UTILIZING ELEVATED TEMPERATURE AND COLLAPSIBILITY TESTING

by

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Western Michigan University, 2004

This research study examines the effects of refractory coatings on a shell sand using laboratory testing equipment as opposed to the more laborious and time consuming processes of molding, melting, filling, shakeout, and obtaining dimensions of actual castings. As of today, there have not been any such laboratory test methods. This research project focused on quantifying distortion, mass change, and impact strength found in refractory coated shell sand. The equipment used was the thermal distortion tester (TDT) and a modified impact tester. The thermal distortion curves (TDC), mass change, and impact strength are provided and compared for all systems studied. The results from thermal distortion testing show that refractory coatings reduce distortion in sand cores and molds. The refractory coatings also prevent sand/binder losses and expansion defects. Finally, the refractory coatings did not affect the shakeout/collapsibility of the sand system.

TABLE OF CONTENTS

Table of Contents—continued

APPENDICES

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION & PURPOSE

Shell sand cores and molds are important parts of metal casting technology and their behavior, when in contact with molten metal, is of great interest. Every year, the foundry industry spends millions of dollars on refractory coatings for these sand systems. These coatings have been used to improve surface finish and reduce thermal expansion defects (such as veining) and un-bonded sand defects (such as erosion). In addition, it is important to assess the addition of coatings in terms of productivity issues. Specifically, it is important to understand how coated systems shake out of a casting.

According to Iyer et al., 2001, directional heating of sand composites (mold and core media) will generate anisotropic thermal gradients in the materials. Additionally, when a sand composite comes into contact with molten metal, the heat transferred causes thermo-chemical reactions that result in dimensional changes in the composite. These dimensional changes or thermal distortions are attributable to simultaneous changes in both the sand and the binder at all temperatures (Iyer et al., 2001). Therefore, it is of interest to see the effect of different coating types of varying thickness when placed between the mold/metal interface.

Thus far, the choice for evaluating the effects of binder systems, binder levels, sand types, coatings, and other variables of the mold/core making process is the erosion wedge test (Henry et al., 2003). Although the erosion wedge test is not an official testing method, it is considered a "standard" in the cast metals industry. Many of the previous studies have been conducted using this test casting method. However, it is laborious, costly, and includes the time consuming processes of molding, melting,

filling, shakeout, and obtaining dimensions the actual castings. To avoid having to perform these costly processes, this study compares refractory coatings on disc shaped shell sand utilizing elevated temperature and collapsibility testing through the use of laboratory testing equipments. The thermal issues can be addressed in thermal distortion testing (Iyer et al., 2001). A measure of shakeout (collapsibility testing) will be collected in this study using a modified impact testing method.

Results from a previous study conducted on shell sand have shown that coatings do prevent erosion type defects (Ramrattan et al., 2000). Several limitations in the study mentioned include (1) the use of alcohol based coating but water based coatings have been gaining popularity as they are more environmentally friendly, (2) thickness of the coatings were not quantified, and (3) the study was conducted only at aluminum fill temperature.

Shell sand system was preferred over several of the no bake binder sand binder systems due to its thermal stability (Keil et al., 1999). A more thermally stable base system would reduce extraneous variables that could corrupt the thermal distortion data and thus, amplify the effects of the coatings studied. A more detailed explanation on the thermal characteristics of the shell binder system is available in Appendix A.

In the present work, the shell system was studied with two different types of refractory coatings – mica/graphite (M/G) and zircon (Z). The M/G coating is suggested to be more thermally insulating while the Z coating is touted as being thermally conductive (Guyer, 2003). Typical foundry coating thickness is 0.006 inches; however, the accuracy of thickness measurement is ±0.001 inch (Guyer, 2003). Thus, specimens used in the study would be coated at thickness levels of 0.003, 0.006, and 0.009 inches. After thermal exposure, the test specimen is still

intact allowing determination of additional valuable information that can be gained after thermal exposure. The valuable information includes the impact strength, visual analysis for cracks (which in the metal casting process, could result in veining), and mass change measurement (that relates to pyrolysis of binder bridges and the amount of loose, unbonded sand generated at the mold metal interface) (Ramrattan et al., 1997). Control specimens were tested for thermal distortion, impact strength and percent mass change. Thermal distortion (mold wall movement), impact strength (shakeout/collapsibility), percent change in mass (degradation losses), and veining (cracks) have a bearing on casting quality (Ramrattan et al., 1997).

The objectives of the study were three fold:

- To determine if there is a difference between the coatings types
- To determine if there is a difference in coatings at aluminum and cast iron fill temperatures
- To determine if small changes in coating thickness have an effect on thermal distortion and impact strength

CHAPTER II

METHODOLOGY

To ensure that the study would be executed logically, a factorial design of 2 coatings (M/G and Z) by 2 temperatures (aluminum and cast iron) by 3 coating thicknesses (0.003, 0.006, and 0.009 inch) with ten replicates per cell was employed.

The testing procedure consisted of 4 major steps: (1) Preparation of disc-shaped specimens, (2) Coating of specimens according to type and thickness, (3) TDT, and (4) Observation of physical changes, impact strength, and mass changes. (Note: All specimens were prepared and tested under laboratory conditions. Ambient conditions were: temperature controlled at 75°F (24±1°C), relative humidity was controlled at 50±2%).

Preparation of Disc Shaped Shell Specimens

Shell specimens were prepared using washed and dried round grain silica sand. See Table 1 for details.

Source	**AFS/gfn**	**Shape**	**Screens**	**% Resin**	**Roundness/ Sphericity (Krumbein)**	**pH**	**Acid demand (pH-7)**
IL	90	Round	3	3	0.8/0.8	Neutral	<1

Table 1. Properties of Sand

The shell sand disc specimens were prepared employing the coremaking techniques used in industry (Carey et al., 1995). A disc-making pattern was preheated while being held between heated platens thermostatically controlled at 450°F. The coated sand was poured into three cavities of the pattern, struck off, and allowed to cure for 3 minutes, after which the specimens were removed from the fixture (Figure 1 and Figure 2). The curing time is subjective and is based on the color of the specimens after they are removed from the pattern. The color of the surface of the specimens should be golden yellow, which is a clear indication that they are strong and thoroughly cured (Carey et al., 1995).

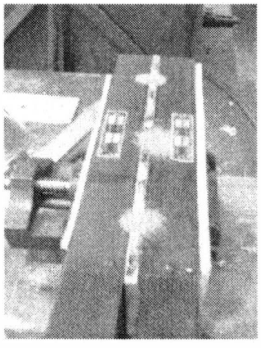

Figure 1. Specimens Being Cured

Figure 2. Specimens Being Removed from Pattern

Refractory Coating of Disc Shaped Shell Specimens

The dipping process described below is a reference of Guyer, 2003.

Two gallons of each experimental refractory coating (M/G and Z) were collected from standard production lots of the respective coatings at the manufacturer's facility. These samples were isolated and used exclusively for this experiment.

Dry deposit (coating) was determined by trial and error. A serial dilution was run on each refractory coating and extra discs were hand dipped, dried, and evaluated for refractory coating deposit. It is necessary to determine dry thickness levels on sample discs/specimens because the dry refractory coating deposit test is a destructive test under these conditions. After the discs were hand dipped into the refractory coating, they were placed horizontally (refractory coated surface up) in a forced air oven and dried at 125°F (52.0 ± 1°C) for one hour. Then, the refractory coating dry deposits of the sample discs were determined using a dial thickness gage. The gage was zeroed on the refractory coated surface, a small section of refractory coating was removed from the surface and the difference between the original surface and the substrate was then measured to the nearest 0.001 inch. Once the desired dry refractory coating deposit was achieved on a sample disc, the experimental discs were hand dipped (approximately 1 second) in the same diluted refractory coating and dried.

Thermal Distortion Testing (TDT)

The thermal distortion tester (TDT) was used in this experiment to expose each 50 mm diameter and 8 mm-thick disc specimens to a hot surface, either at

aluminum (1400°F (760°C)) or cast iron fill temperatures (2350°F (1288°C)) for 3 minutes. The test duration is set based on the time it takes for the molten metal to solidify. This solidification time varies with the size of a casting and metal represented. A predetermined load on the TDT can be adjusted to approximate a specified load from molten metal acting on a mold (head pressure). Information on the operation of the TDT and computation of test load is available in Appendix A. For this study the load was kept constant during TDT at 0.73 lb (332 g) and the length of TDT was 3 minutes.

Observations

Change in Mass

Prior to TDT each specimen was weighed. Following TDT the surface of the specimen was blown with 20-psi (0.14 MPa) air pressure to remove any loose sand grains. The specimens were then again weighed, and the percent change in mass was recorded. Following weighing, the specimens were visually examined for signs of thermally induced cracking of the surface, and loss of sand where contact was made with the hot surface, and any other discolorations or visual observations. The percent change in mass was calculated based upon the weight before and after as a percent of the weight before. All percent change in mass values represents the percentage of weight lost.

Impact Strength

An impact testing machine (Tinius Olsen) equipped with a disc specimen holder (Figure 3) was used to measure the strength of the sand specimens prior to the

TDT, and after the TDT.

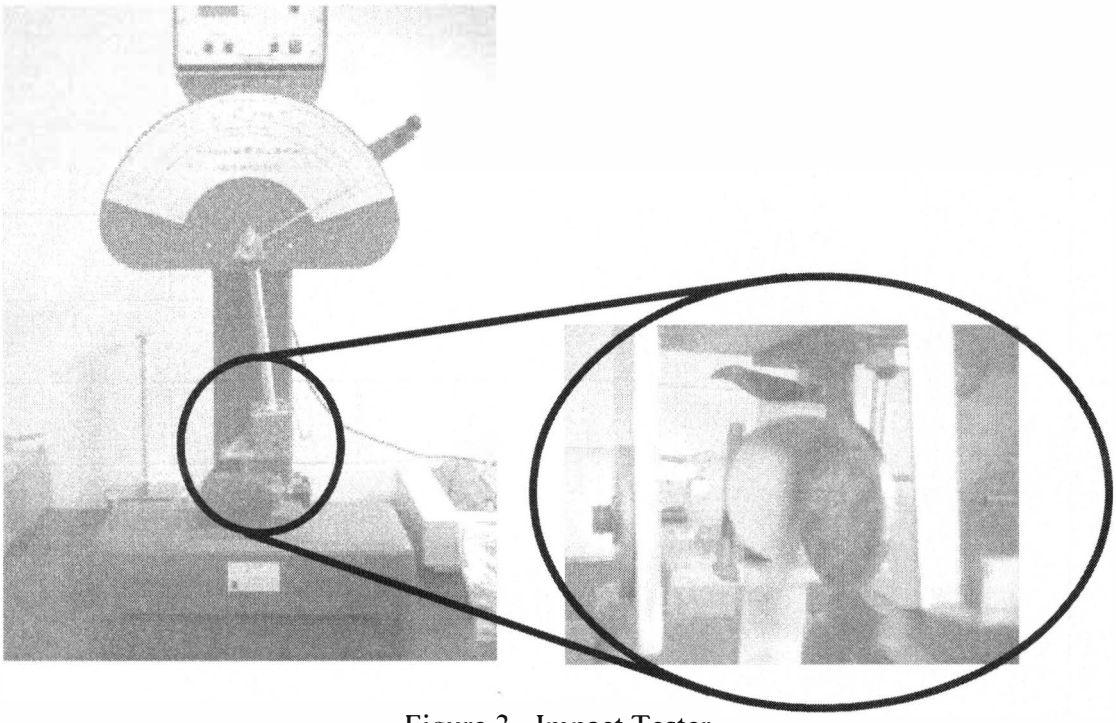

Figure 3. Impact Tester

The disc-shaped specimen was fitted into a specimen holder on the impact testing machine and was supported on its ends. It was then subjected to impact energy by dropping a uniform with a 2.00 mm thick rounded edge blade across its diameter. A load-cell electronically sensed the specimen failure, digitally displaying the results, and the maximum energy to failure (inch-pounds) was recorded as impact strength.

CHAPTER III

RESULTS & DISCUSSION

Analysis subsequent to testing and data collection revealed that the mean mass of M/G coatings did not vary between the independent variable coating thickness levels (0.003,0.006,0.009) specified ($p = 0.161$)[1]. On the contrary, the mean mass of the Z coating were statistically different for the three thickness levels ($p = 0.001$)[2]. Since there is no significant difference between the mean mass of the M/G coatings and there is a significant difference between the Z coatings, that poses a problem in data for TDT, percent mass change, and impact strength testing because of the inability to differentiate between the thickness levels for both coatings. Thus, the variable coating thickness was removed and is disregarded from further discussion. With the suggestion from the industrial coating specialist, the study was repeated at one thickness level of 0.006 inches as the typical foundry coating thickness. All statistical analysis was performed with $\alpha = 0.05$ and other factors such as operator, time of coating, and environmental conditions were blocked or held constant. Model assumptions, such as normality, were checked for each test employed.

After the removal of thickness as an independent variable, the results for thermal distortion, percent mass change, and impact strength were easier to differentiate. Results from the repeated study for systems tested are shown in Table 2.

[1] Detailed statistical analysis is available in Appendix D-1.
[2] Detailed statistical analysis is available in Appendix D-1.

Systems	Test Temp. (°F)	Thermal Distortion Range (in.) @ 332g for 3 minutes		% Change in Mass[3]		Impact Strength[4] (in.-lb)	
		Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
C	75	Not Applicable	Not Applicable	Not Applicable	Not Applicable	5	2
CM/G		Not Applicable	Not Applicable	Not Applicable	Not Applicable	6	3
CZ		Not Applicable	Not Applicable	Not Applicable	Not Applicable	6	2
C_{AL}	1400	0.003	0.0004	0.45	0.21	5	2
M/G_{AL}		0.003	0.0003	0.24	0.21	5	2
Z_{AL}		0.003	0.0005	0.20	0.21	5	2
C_{FE}	2350	0.005	0.0009	1.28	0.17	5	3
M/G_{FE}		0.004	0.0010	0.40	0.19	5	2
Z_{FE}		0.004	0.0002	0.36	0.13	6	2

Table 2. Physical and Thermo-Mechanical Properties of the Shell Discs Specimens

Results from TDT, impact strength, and percent change in mass are presented according to coating type and control specimens, in Table 2.

[3] All percent change in mass values represents the percentage of weight lost.
[4] Impact strength is also referred to as the maximum energy to failure.

TDT[5]

The mean distortion data from TDT is presented in the form of thermal distortion curves (TDC). The measure of thermal distortion is taken as an absolute measure from the highest point to the lowest point of a TDC (Ramrattan et al., 1997). The TDC's for all systems tested showed undulations that indicate thermo-mechanical and thermo-chemical changes in the binder system at elevated temperature (Iyer et al., 2001). Figure 4 shows TDC for controls and coated systems at aluminum and iron temperatures.

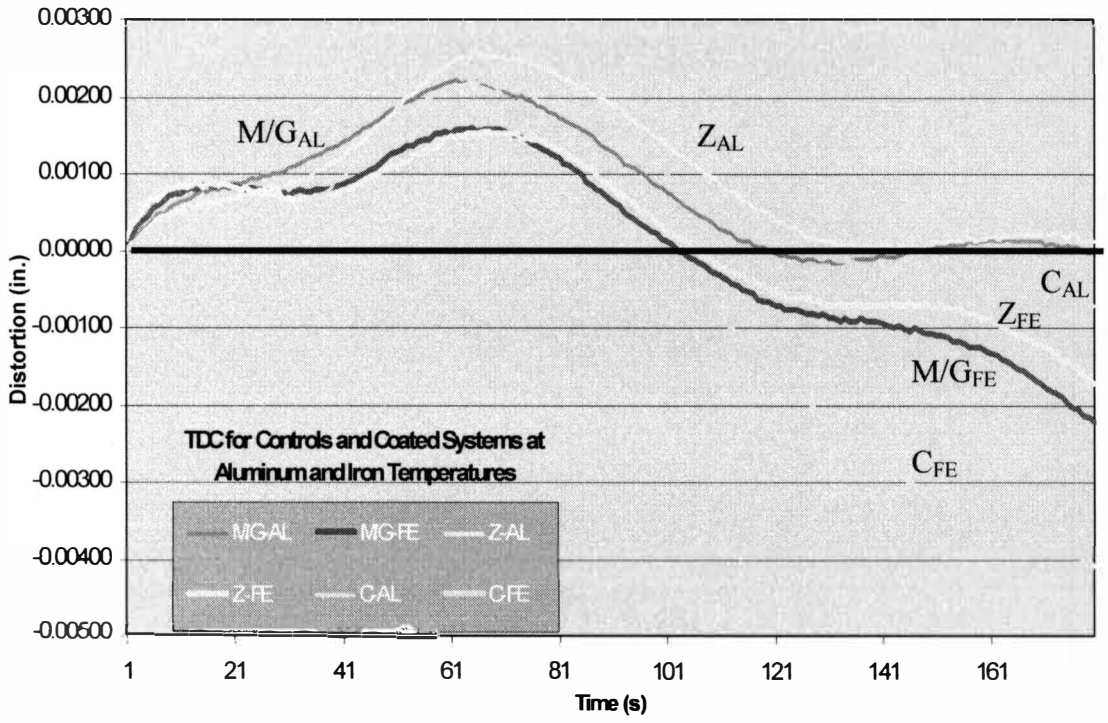

Figure 4. TDC for C_{AL}, C_{FE}, M/G_{AL}, M/G_{FE}, Z_{AL}, and Z_{FE}

[5] Detailed statistical analysis presented in this section is available in Appendix C.

All curves had an initial expansion (upward movement of TDC) before plastic deformation (downward movement of TDC).

More specifically, for coated systems (M/G_{AL} and Z_{AL}) tested at aluminum temperature (1400°F (760°C)) there was continuous expansion for the first ~65 seconds followed by plastic deformation for the next ~60 seconds before the curves stabilized. The uncoated control system (C_{AL}) had a similar TDC but this uncoated system showed further plastic deformation towards the end of the test.

In addition, systems tested at cast iron temperature (2350°F (1288°C)) showed expansion for the first ~70 seconds. However, there was a primary and a secondary expansion phase (See curves C_{FE}, M/G_{FE}, and Z_{FE}). This was followed by plastic deformation over the rest of the test. The coated specimens did temporarily level out after an additional ~50 seconds but continued plastic deformation for the remainder of the test period. After the initial expansion, the C_{FE} system exhibited only plastic deformation.

By looking at the TDC in Figure 4, it appears that there is no significant difference between coating types at the aluminum test temperature (M/G_{AL} and Z_{AL}) and at the cast iron test temperature (M/G_{FE} and Z_{FE}). This was verified statistically with the p-values of 0.426 and 0.445, respectively.

When comparing the refractory coated systems to the uncoated control systems (C_{AL}) tested at the same temperature, the results were significant ($p = 0.013$). In other words, the C_{AL} specimens had greater mean thermal distortion than the refractory coated systems. It was also apparent in Figure 4 that the TDC for C_{FE} was different from the rest of the curves. Data for C_{FE} from TDT showed that this system had the greatest thermal distortion range. Statistical analysis indicated that there was a significant difference for the C_{FE} when compared to all other systems tested ($p =$

0.000). Temperature and coating type were also statistically analyzed to check for significance and interaction. The results from the analysis indicate that there is a significant difference ($p = 0.000$) in temperature (AL and FE) and no significant difference ($p = 0.301$) for coating type with respect to thermal distortion. In other words, temperature is a factor in thermal distortion while coating type is not. In addition, there was no interaction between those two variables.

Previous TDT studies that delved into uncoated shell systems were tested at aluminum fill temperature (Iyer et al., 2001 and Ramrattan et al., 2003). Comparing the present data for C_{AL} to previous studies, a similar trend was observed.

Even though the samples were cured prior to testing, some residual reactivity is seen by the way of undulation on the TDC. If the application of heat causes further cross-linking reaction in the specimen, it will generate gases as novolac-curing reactions typically do and as a result, will cause some distortion in the specimen (Iyer et al., 2001). Due to the inherent thermal stability of the resin, it is expected that there should be minimal increases in the region of thermal stability and more in the ranges where decomposition is occurring (Iyer et al., 2001).

Mass Change[6]

The uncoated control systems (C_{AL} and C_{FE}) had significant mean mass loss when compared to the coated systems (Figure 5). Further, the percent changes in mass between C_{AL} and C_{FE} systems were significantly different ($p = 0.000$). Therefore, it was inferred that C_{AL} had less loss due to lower thermal stress. Mass change was not significant among the coated systems regardless of coating type ($p =$

[6] Detailed statistical analysis for this section is available in Appendix D.

0.505). This would indicate that coatings offered some thermal resistance to mass change. Despite that, a higher percentage of mass loss was observed to be occurring at the higher testing temperature ($p = 0.011$) (Figure 5). In addition, no interactions were found for the variables temperature and coating type.

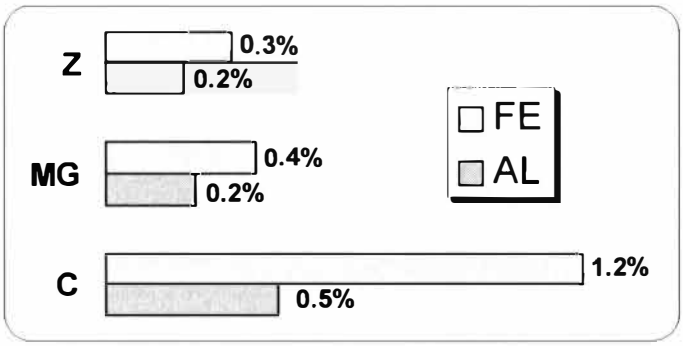

Figure 5. Bar Graphs for Percent Change in Mass for All Systems Tested

Observations from the heat affected zone on the surface of tested specimens revealed that the uncoated control systems had visible sand losses and crack propagation. Typical refractory coated and uncoated specimens before and after TDT and impact testing is shown in Figure 6.

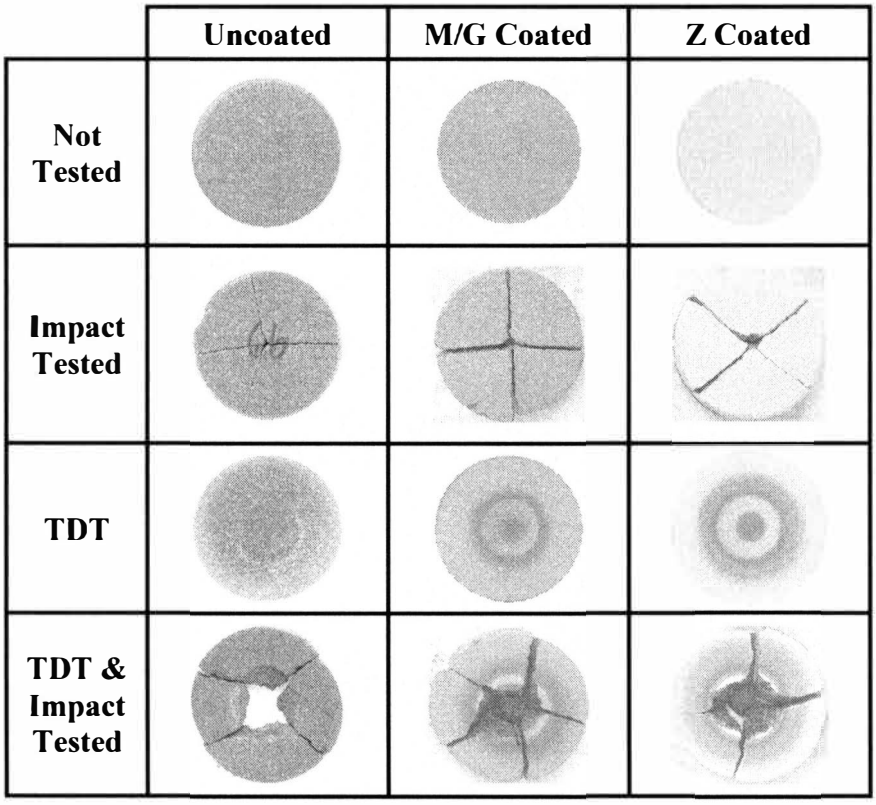

Figure 6. Typical Refractory Coated and Uncoated Specimens Before and After TDT and Impact Testing

For all uncoated control systems tested, the hot surface/specimen interface showed black to brown discolorations due to various levels of binder degradation (Figure 6) (Ramrattan et al., 1997). In addition, sand binder losses were evident at the hot surface/specimen interface where binder bridges pyrolyzed and sand grains broke loose; this was apparent in C_{AL} and especially C_{FE}. Expansion cracks were macroscopically evident on the uncoated control systems and to a much lesser extent on coated systems. The crack propagation was more pronounced in C_{AL} but especially on C_{FE}. For the coated specimens there was nothing more than faint cracks on M/G and Z coatings regardless of test temperature.

Impact Strength[7]

Impact strengths before TDT relate to handling of the core/mold material after core/mold production, prior to pouring. The impact strengths after TDT testing relate to shakeout/collapsibility characteristics (Ramrattan et al., 1997).

The uncoated control systems (C_{AL} and C_{FE}) were not significantly different in strength when compared to the coated systems at their respective testing temperatures. (Statistical analysis for impact strength test for C_{AL} versus M/G_{AL} and Z_{AL} yielded a p-value of 0.281 while C_{FE} versus M/G_{FE} and Z_{FE} yielded a p-value of 0.957.) Further, the mean impact strength between the two uncoated control systems was not significantly different ($p = 0.812$). Impact strength was also not significantly different between the coated systems regardless of coating type ($p = 0.533$). Interaction between temperature and coating type were not present for impact strength. It must be noted that the C_{FE} specimen was not significantly different from all other systems (coated or uncoated) in impact strength ($p = 0.652$). This would indicate that the addition of a coating offered negligible impact resistance and that strength was derived primarily from the shell sand system.

[7] Detailed statistical analysis for this section is available in Appendix E.

CHAPTER IV

LIMITATIONS

The effects of cast metal chemistry on coatings and shell systems were not considered in this study. The work in this paper represents shell coated specimens as examples of application of the TDT in conjunction with change in mass and impact strength measurements, and visual observation. There are numerous other chemical binder systems from which additional data could be gathered to learn more about their thermal properties.

The work in this paper represents the data for two coating types at temperatures representing aluminum and cast iron fill at a constant pressure. Additional work could be done at different loads and different temperatures simulating other alloys, and pressures representative of larger or smaller castings. The relationship between TDT data and casting dimensions requires actual casting trials be conducted in order to validate the TDT test data.

CHAPTER V

CONCLUSIONS

The thermo-mechanical changes brought forth in this study are in the forms of TDC, mass loss, impact strength, and cracks on the surface of the test specimen (coated and uncoated). For thermal distortion, the M/G and Z coatings were similar. Cast iron temperature did cause higher mean thermal distortion for both the coated and uncoated shell systems when compared to aluminum temperature. However, both the coatings did reduce thermal distortion at cast iron temperature.

Mean percent mass changes were the same for both the M/G and Z coatings. In addition, only faint cracks were observed on M/G and Z coatings regardless of test temperature. The faint cracks are undoubtedly the result of expansion/contraction differentials between the coating and sand composite. The positive effects of applying coatings to the shell system were shown in the reduction of mass losses and surface cracks. Higher mass losses and surface cracks were prominent on the uncoated control systems. For these uncoated systems, cast iron temperatures did cause greater mass loss and expansion cracks compared to that found at aluminum temperature. Therefore, coating can help in the prevention of cuts and washes and erosion/inclusion type defects.

There was no significant difference between the M/G and Z coatings for the mean impact strength. In addition, test temperature was also not a significant factor. The coatings applied did not hinder or resist shakeout of the shell system studied.

In short, this study has found that the two coatings studied did reduce thermal distortion considerably at cast iron temperature. At aluminum temperature, coatings are do not appear to be necessary since the findings in this study indicated no

significant difference in the mean thermal distortion between the controls and coated specimens. Temperature was a significant factor regarding mass losses since that would lead to erosion type defects. This was evident again, only at cast iron temperature and coating did help reduce mass losses. Coatings also did not cause the need for additional energy for shakeout based on the results from impact strength test.

CHAPTER VI

RECOMMENDATIONS

Since the present study was not able to distinguish between the small changes in coating thickness levels, a future study could be conducted comparing thickness levels of 0.01 and 0.003 inches. The results from this study indicated that coatings were more effective at cast iron fill temperature. It is recommended that any future study be conducted at cast iron or at a higher fill temperature, such as steel, with pressure head representing larger castings. Impact testing may not be necessary, as this study has shown that coatings would not require additional energy for shakeout.

Sand that is more "wetable" (40 to 50 AFS/gfn for shell systems) was also recommended by coating specialists for a better coating penetration. The preferred coating penetration is 2 to 3 sand grains. Due to the finer sand that was used in this study, the coating specialists were suspicious that sand grain penetration and thickness level of the coatings were not at the levels specified for the specimens coated.

Most importantly, an improved or automated dipping and coating thickness-gauging technique is needed to reduce variation in the coating process and thickness.

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Appendix A

Thermal Characteristics of Shell Binder System

Shell resin is a typical, acid catalyzed novolac type resin. These resins are low molecular weight polymers with a well-defined range of melt points and viscosities. The resin is cross-linked with the use of a thermosetting agent, like hexa, and the application of heat. These resins are generally regarded as thermally stable, meaning that some property of a material using this resin does not change with time at a given temperature (Knop et al., 1985). In the present work, thermally stable refers to a time zone where minimal/no heat induced thermo-chemical reactions are occurring. These resins are quite stable up to 518°F (270°C) after which thermal degradation begins (Knop et al., 1985). It is also reported that the thermo-chemical degradation of novolacs in shell is a thermal-oxidative process regardless of whether the pyrolysis reaction occurs in an oxidative or inert atmosphere (Knop et al., 1985). Between 572°F (300°C) and 1112°F (600°C), the rate of degradation increases with the evolution of gaseous components. Beyond 1112°F (600°C), breakdown of the phenolic structure are evident (Knop et al., 1985).

Appendix B

Thermal Distortion Testing Procedure

To operate the TDT (Figure B- 1), the electrical power was switched on and the temperature control was adjusted to represent a specific molten metal fill temperature [in this experiment aluminum fill temperature was set at 1400°F (760°C) and cast iron fill temperature was set at 2350°F (1288°C)].

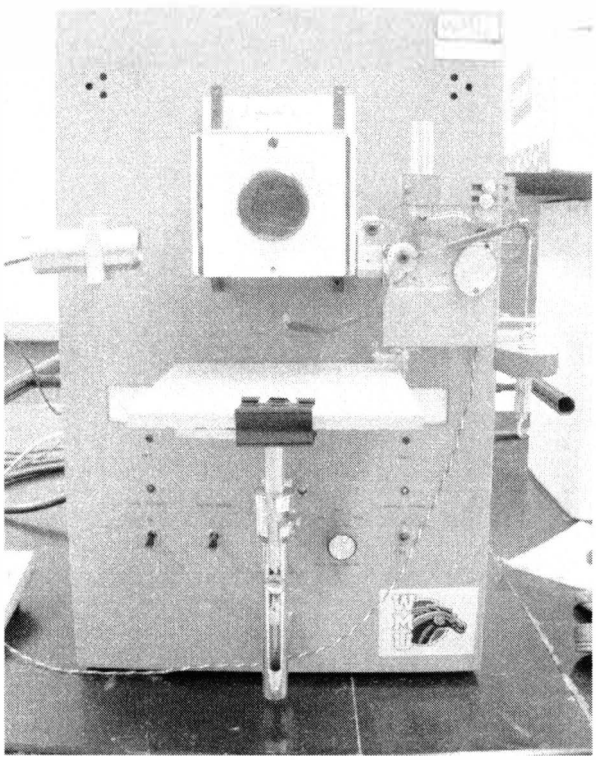


Figure B- 1. TDT

A predetermined load on the TDT can be adjusted to simulate a specified force of molten metal acting on a mold (head pressure). The load used during TDT was 0.73 lb (332 g); this was computed by multiplying the contact area of TDT hot surface by the head pressure (Head Height * Metal Density). The test duration was set at 3 minutes per specimen.

The computer and data acquisition system was switched on for controlling,

monitoring and plotting graphs of temperature/time versus distortion. The temperature was controlled using an optical pyrometer that is focused on the hot surface. The test piece was inserted into a specimen cradle (Figure B- 2), designed for holding the disc shaped specimen. The specimen cradle is placed onto a lever arm loading mechanism to become a pivoting holder (gimbal) (Figure B- 3).

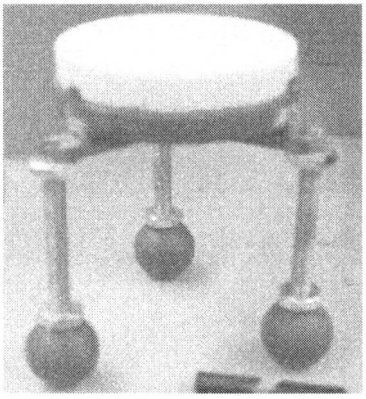


Figure B- 2. Specimen on Cradle

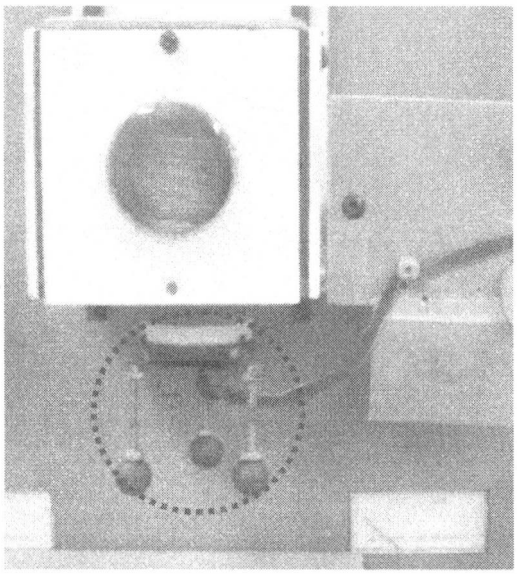


Figure B- 3. Gimbal on Lever Arm

The test piece was then automatically raised until direct symmetrical contact

was made with the 2.00 cm diameter hot surface. This simultaneously engages the linear voltage displacement transducer that measures the distortion. The data acquisition system automatically logged and plotted the distortion versus time/temperature curve or thermal distortion curve (TDC). The length of the TDT was two minutes; however, this can be varied. During the test, the predetermined load chosen to represent the force of molten metal pressing against the mold/core wall presses the gimbal in contact with the circumference of the specimen and holds the top of the specimen against the hot surface (Figure B- 4).

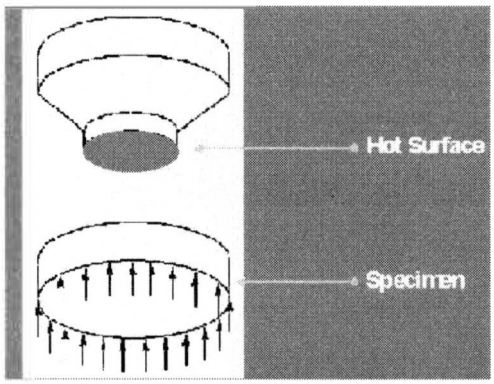


Figure B- 4. Circumferential Loading of Specimen onto the Hot Surface

Any downward movement of the gimbal is recorded as expansion (and appears as upward movement when plotted). Any upward movement of the gimbal, due to the specimen becoming thermoplastic and plastically deforming around the hot surface is recorded as distortion (and appears as downward movement when plotted). While it is possible to differentiate between expansion and plastic deformation separately from the curves, in the final analysis in this investigation, the authors chose to record the distortion in the tables as the total of the expansion plus plastic deformation, since movement of mold or core material in either direction could be detrimental to casting quality and dimensional reproducibility.

Appendix C

Statistical Results for Thermal Distortion

Appendix C-1

Comparing thermal distortion (inches) of M/G_{AL} and Z_{AL}.

TD versus Coating Type

H_0: Mean thermal distortions of coated systems (M/G_{AL} and Z_{AL}) at aluminum fill temperature are statistically not different.

H_1: Mean thermal distortions of coated systems (M/G_{AL} and Z_{AL}) at aluminum fill temperature are statistically different.

Factor	Type	Levels	Values	
Coating	fixed	2	1 2	where value 1 represents M/G and 2 represents Z coating

Analysis of Variance for TD, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Coating	1	0.0000001	0.0000001	0.0000001	0.67	0.426
Error	16	0.0000024	0.0000024	0.0000002		
Total	17	0.0000025				

Appendix C-2

Comparing thermal distortion (inches) of M/G_{FE} and Z_{FE}.

TD versus Coating Type

H_0: Mean thermal distortions of coated systems (M/G_{FE} and Z_{FE}) at cast iron fill temperatures are not statistically different.

H_1: Mean thermal distortions of coated systems (M/G_{FE} and Z_{FE}) at cast iron fill temperatures are statistically different.

Factor	Type	Levels	Values	
Coating	fixed	2	1 2	where value 1 represents M/G and 2 represents Z coating

Analysis of Variance for TD, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Coating	1	0.0000005	0.0000005	0.0000005	0.61	0.445
Error	18	0.0000133	0.0000133	0.0000007		
Total	19	0.0000137				

Appendix C-3

Comparing thermal distortion (inches) of C_{AL} (uncoated control) and coated systems

TD versus Coating Thickness

H_0: Mean thermal distortions of coated and uncoated systems at aluminum fill temperatures are not statistically different.

H_1: Mean thermal distortions of coated and uncoated systems at aluminum fill temperatures are statistically different.

Factor	Type	Levels	Values	
Coating	fixed	2	0.000 0.006	where value 0.000 represents uncoated control systems and 0.006 represents coated systems

Analysis of Variance for TD, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Coating	1	0.0000011	0.0000011	0.0000011	6.96	0.013
Error	31	0.0000049	0.0000049	0.0000002		
Total	32	0.0000060				

Appendix C-4

Comparing thermal distortion (inches) of uncoated control system (C_{FE}) tested at cast iron fill temperature to all other systems (C_{AL}, M/G_{AL}, Z_{AL}, M/G_{FE}, and Z_{FE})

TD versus Coating Type

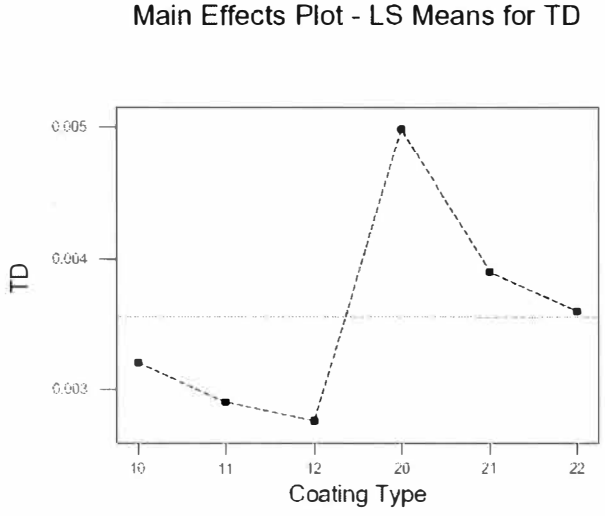
H_0: Mean thermal distortions of C_{FE} are not statistically different from C_{AL}, M/G_{AL}, Z_{AL}, M/G_{FE}, and Z_{FE}.

H_1: Mean thermal distortions of C_{FE} are statistically different from C_{AL}, M/G_{AL}, Z_{AL}, M/G_{FE}, and Z_{FE}.

Factor	Type	Levels	Values
Coating	fixed	6	10 11 12 20 21 22 where value 10 represents C_{AL}, 11 represents M/G_{AL}, 12 represents Z_{AL}, 20 represents C_{FE}, 21 represents M/G_{FE}, 22 represents Z_{FE}

Analysis of Variance for TD, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Coating	5	0.0000431	0.0000431	0.0000086	19.03	0.000
Error	62	0.0000281	0.0000281	0.0000005		
Total	67	0.0000712				



Tukey's post hoc test is available on the next page.

Appendix C-4 (continued)

Tukey Simultaneous Tests
Response Variable TD
All Pairwise Comparisons among Levels of Coating

Coating = 10 subtracted from:

Level Coating	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
11	-0.000300	0.000275	-1.092	0.8829
12	-0.000450	0.000295	-1.527	0.6486
20	0.001800	0.000246	7.322	0.0000
21	0.000700	0.000275	2.547	0.1266
22	0.000400	0.000275	1.455	0.6933

Coating = 11 subtracted from:

Level Coating	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
12	-0.000150	0.000319	-0.4697	0.9970
20	0.002100	0.000275	7.6408	0.0000
21	0.001000	0.000301	3.3214	0.0180
22	0.000700	0.000301	2.3250	0.1999

Coating = 12 subtracted from:

Level Coating	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
20	0.002250	0.000295	7.634	0.0000
21	0.001150	0.000319	3.601	0.0079
22	0.000850	0.000319	2.662	0.0980

Coating = 20 subtracted from:

Level Coating	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
21	-0.001100	0.000275	-4.002	0.0023
22	-0.001400	0.000275	-5.094	0.0001

Coating = 21 subtracted from:

Level Coating	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
22	-0.000300	0.000301	-0.9964	0.9174

Appendix C-5

Comparing test temperatures (AL and FE) and coating types (M/G and Z)

TD versus Temperature, Coating Type

H_{01}: Mean temperatures of AL and FE are not a significant factor in thermal distortion.

H_{11}: Mean temperatures of AL and FE are a significant factor in thermal distortion.

H_{02}: Coating type is not a significant factor in thermal distortion.

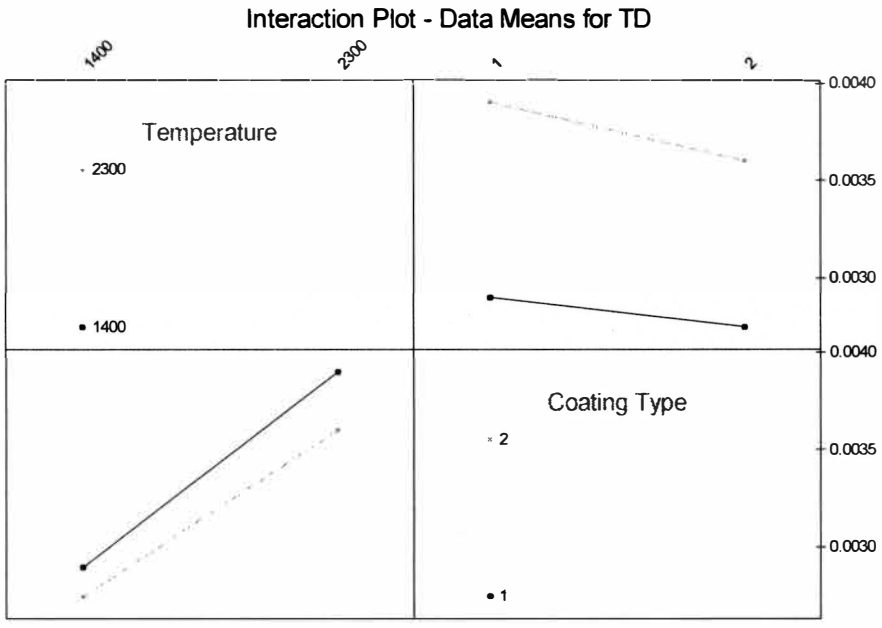
H_{12}: Coating type is a significant factor in thermal distortion.

Factor	Type	Levels	Values	
Temperature	fixed	2	1400 2300	
Coating	fixed	2	1 2	where value 1 represents M/G and 2 represents Z coating

Analysis of Variance for TD, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Temperature	1	0.0000080	0.0000082	0.0000082	18.13	0.000
Coating	1	0.0000005	0.0000005	0.0000005	1.10	0.301
Error	35	0.0000158	0.0000158	0.0000005		
Total	37	0.0000242				

Appendix C-6


Interaction Plot - Data Means for TD
1400
2300
1
2
Temperature
2300
1400
Coating Type
2
1
0.0040
0.0035
0.0030
0.0040
0.0035
0.0030

Appendix D

Statistical Results for Mass Change

Appendix D-1

Comparing mean thickness of coatings at levels 0.003, 0.006, and 0.009 inches.

Mean M/G Mass versus Thickness

H_0: Mean mass of M/G specimens are not statistically different at all thickness levels.

H_1: Mean mass of M/G specimens are statistically different at some thickness levels.

Factor	Type	Levels	Values
Thickness	fixed	3	3 6 9

Analysis of Variance for After, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Thickness	2	0.30900	0.30900	0.15450	1.89	0.161
Error	57	4.66750	4.66750	0.08189		
Total	59	4.97650				

Mean Z Mass versus Thickness

H_0: Mean mass of Z specimens are not statistically different at all thickness levels.

H_1: Mean mass of Z specimens are statistically different at some thickness levels.

Factor	Type	Levels	Values
Thickness	fixed	3	3 6 9

Analysis of Variance for After, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Thickness	2	1.11600	1.11600	0.55800	7.84	0.001
Error	57	4.05650	4.05650	0.07117		
Total	59	5.17250				

Appendix D-2

Comparing mean % mass change between uncoated control system (C_{AL} and C_{FE}).

% Mass Change versus Temperature

H_0: Mean % mass change of C_{AL} and C_{FE} specimens are not statistically different.

H_1: Mean % mass change of C_{AL} and C_{FE} specimens are statistically different.

Factor	Type	Levels	Values
Temperature	fixed	2	1400 2300

Analysis of Variance for % Mass C, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Temperature	1	5.1253	5.1253	5.1253	146.24	0.000
Error	28	0.9813	0.9813	0.0350		
Total	29	6.1067				

Appendix D-3

Comparing temperature and coating type with respect to mean % mass change.

% Mass Change versus Temperature, Coating Type

H_{01}: Temperatures is not a significant factor in the % mass change data.

H_{11}: Temperatures is a significant factor in the % mass change data.

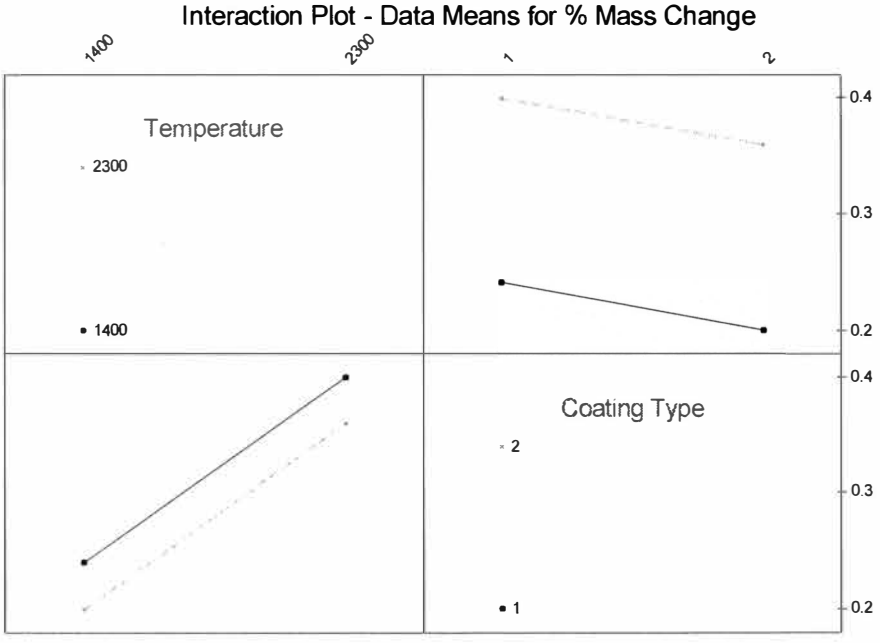
H_{02}: Coating type is not a significant factor in the % mass change data.

H_{12}: Coating type is a significant factor in the % mass change data.

Factor	Type	Levels	Values	
Temperature	fixed	2	1400 2300	
Coating	fixed	2	1 2	where value 1 represents M/G and 2 represents Z coating

Analysis of Variance for % Mass C, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Temperature	1	0.23584	0.24178	0.24178	7.25	0.011
Coating	1	0.01511	0.01511	0.01511	0.45	0.505
Error	35	1.16800	1.16800	0.03337		
Total	37	1.41895				



Appendix E

Statistical Results for Impact Strength

Appendix E-1

Comparing mean impact strength between coated and uncoated specimens at the respective fill temperatures

Cast Iron Fill Temperature

Impact versus Coating Type

H_0: Mean impact strength of coated systems (M/G_{FE} and Z_{FE}) and uncoated systems (C_{FE}) at cast iron fill temperatures are statistically not different.

H_1: Mean impact strength of coated systems (M/G_{FE} and Z_{FE}) and uncoated systems (C_{FE}) at cast iron fill temperatures are statistically different.

Factor	Type	Levels	Values	
Coating	fixed	3	0 1 2	where value 0 represents C_{FE}, 1 represents M/G_{FE}, and 2 represents Z_{FE}

Analysis of Variance for Impact, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Coating	2	14.338	14.338	7.169	1.32	0.281
Error	32	173.833	173.833	5.432		
Total	34	188.171				

Appendix E-1 (continued)

Aluminum Fill Temperature

Impact versus Coating Type

H_0: Mean impact strength of coated systems (M/G_{AL} and Z_{AL}) and uncoated systems (C_{AL}) at aluminum fill temperatures are statistically not different.

H_1: Mean impact strength of coated systems (M/G_{AL} and Z_{AL}) and uncoated systems (C_{AL}) at aluminum fill temperatures are statistically different.

Factor	Type	Levels	Values	
Coating	fixed	3	0 1 2	where value 0 represents C_{AL}, 1 represents M/G_{AL}, and 2 represents Z_{AL}

Analysis of Variance for Impact, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Coating	2	0.370	0.370	0.185	0.04	0.957
Error	30	127.508	127.508	4.250		
Total	32	127.879				

Appendix E-2

Comparing mean impact strength of uncoated specimens (C_{AL} and C_{FE}) tested at aluminum and cast iron fill temperatures.

Impact (1400) versus Impact (2300)

H_0: Mean impact strength of C_{AL} and C_{FE} are statistically not different.

H_1: Mean impact strength of C_{AL} and C_{FE} are statistically different.

Factor	Type	Levels	Values
Temperature	fixed	2	1400 2300

Analysis of Variance

Source	DF	SS	MS	F	P
Temperature	1	0.30	0.30	0.06	0.812
Error	28	145.07	5.18		
Total	29	145.37			

Appendix E-3

Comparing the significance of coating types (M/G and Z) at aluminum and cast iron fill temperatures with respect to mean impact strength.

Impact versus Coating Type

H_0: Mean impact strength of M/G_{AL} and Z_{AL} are statistically not different from mean impact strength of M/G_{FE} and Z_{FE} specimens.

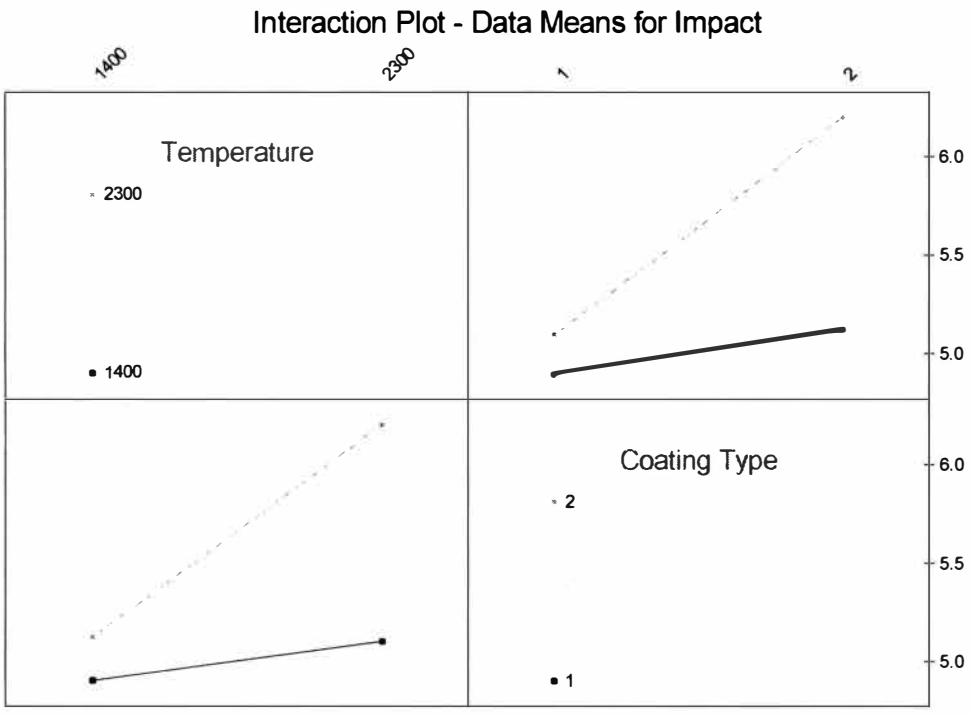
H_1: Mean impact strength of M/G_{AL} and Z_{AL} are statistically different from mean impact strength of M/G_{FE} and Z_{FE} specimens.

Factor	Type	Levels	Values
Coating	fixed	4	11 12 21 22 where 11 represents M/G_{AL}, 12 represents Z_{AL}, 21 represents M/G_{FE}, and 22 represents Z_{FE}.

Analysis of Variance for Impact

Source	DF	SS	MS	F	P
Coating	3	10.28	3.43	0.75	0.533
Error	34	156.28	4.60		
Total	37	166.55			

Appendix E-4


Interaction Plot - Data Means for Impact
1400
2300
1
2
Temperature
2300
1400
Coating Type
2
1
6.0
5.5
5.0
6.0
5.5
5.0

Appendix E-5

Comparing mean impact strength of uncoated control system (C_{FE}) tested at cast iron fill temperature to all other systems (C_{AL}, M/G_{AL}, Z_{AL}, M/G_{FE}, and Z_{FE})

Impact versus Coating Type

H_0: Mean impact strength of C_{FE} are statistically not different from C_{AL}, M/G_{AL}, Z_{AL}, M/G_{FE}, and Z_{FE}.

H_1: Mean impact strength of C_{FE} are statistically different from C_{AL}, M/G_{AL}, Z_{AL}, M/G_{FE}, and Z_{FE}.

Factor	Type	Levels	Values
Coating	fixed	6	10 11 12 20 21 22 where values 10 represents C_{AL}, 11 represents M/G_{AL}, 12 represents Z_{AL}, *20 represents* C_{FE}, 21 represents M/G_{FE}, and 22 represents Z_{FE}

Analysis of Variance for Impact, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Coating	5	16.129	16.129	3.226	0.66	0.652
Error	62	301.342	301.342	4.860		
Total	67	317.471				

Tukey Simultaneous Tests
Response Variable Impact
All Pairwise Comparisons among Levels of Coating

Coating = 10 subtracted from:

Level Coating	Difference of Means	SE of Difference	Adjusted T-Value	Adjusted P-Value
11	0.0333	0.9000	0.0370	1.0000
12	0.2583	0.9652	0.2677	0.9998
20	-0.2000	0.8050	-0.2484	0.9999
21	0.2333	0.9000	0.2592	0.9998
22	1.3333	0.9000	1.4814	0.6772

Appendix E-5 (continued)

Coating = 11 subtracted from:

Level Coating	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
12	0.2250	1.0457	0.2152	0.9999
20	-0.2333	0.9000	-0.2592	0.9998
21	0.2000	0.9859	0.2029	1.0000
22	1.3000	0.9859	1.3185	0.7737

Coating = 12 subtracted from:

Level Coating	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
20	-0.4583	0.9652	-0.4749	0.9969
21	-0.0250	1.0457	-0.0239	1.0000
22	1.0750	1.0457	1.0280	0.9067

Coating = 20 subtracted from:

Level Coating	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
21	0.4333	0.9000	0.4815	0.9967
22	1.5333	0.9000	1.7036	0.5347

Coating = 21 subtracted from:

Level Coating	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
22	1.100	0.9859	1.116	0.8731