A COMPARISON OF BINDER BURNOUT AND MECHANICAL CHARACTERISTICS OF PRINTED AND CHEMICALLY BONDED SAND MOLDS

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ABSTRACT

Various material systems have been created for Binder Jetting of sand molds; however, a formal analysis comparing the materials to commonly used foundry molding materials has not been conducted. In this paper the authors investigate potential differences in the material properties from four different commercially available binders systems for chemically bonded sand molds. Specifically, the authors compared the binder burnout characteristics and the tensile strength of sand created by 3D printing and conventional chemically bonded molding materials. Increased binder content can strengthen the mold but have adverse effect on part quality. Understanding the binder characteristics of printed molds are essential due to the potential defects from large amounts of gas generated from binder while pouring molten metal.

1. INTRODUCTION

1.1. Direct Printing of Sand Casting Molds via Additive Manufacturing

Metal casting is commonly used in manufacturing to create high-quality, low-cost products. While capable of producing a wide range of geometries, the sand casting process inherently constrains the design of a part to geometries that can be produced by forming sand around pre-made patterns and removing the pattern from the sand. Several "design for manufacturing" guidelines must be followed for successful part design for sand casting, including draft angles for pattern release, and pattern geometries that are able to be removed from sand, etc.

Recently, engineers have looked to using Additive Manufacturing (AM) to overcome these geometric restrictions; by processing the sand in an additive context, one is able to directly "print" complex sand molds without the need for a pattern. This pattern-less sand molding approach enables the sand casting of complex mold geometries that could not be made by traditional means thanks to the ability to directly print entire molds (including vents, downsprues, runners, etc.) from a single CAD file (Figure 1) [1,2]. The integration of AM technologies to the foundry industry has increased the efficiency of design and casting production including reducing time and cost associated with the traditional methods of development [3], while still maintaining high accuracy [4].

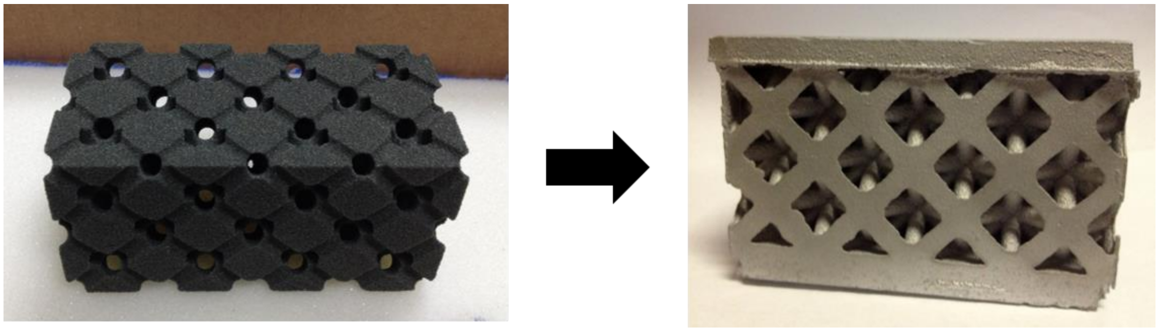

Figure 1. Complex Casting Fabricated via Patternless Sand Molds [2]

For example, in Laser Sintering (LS), printed sand molds are created by scanning the laser across a sand bed to selectively melt a resin coated quartz sand mixture in a layer-by-layer fashion [3,5]. An augmented stereolithography process (Optomec), which selectively cures viscous ceramic-resin slurry via exposure to UV energy, has also been used to directly fabricate sand molds [6].

The most common AM process for the direct fabrication of sand molds is the Binder Jetting process (Figure 2). In this process, layers of spreadable powdered material is bonded together, via the selective inkjetting of a binder solution into a powder bed. A layer of material is spread from the feed tray to the build tray. Binder is jetted over the sand, the build tray lowers, and a new layer is spread. The process is continued layer-by-layer until the part is completed. Figure 2 provides an overview of the Binder Jetting process.

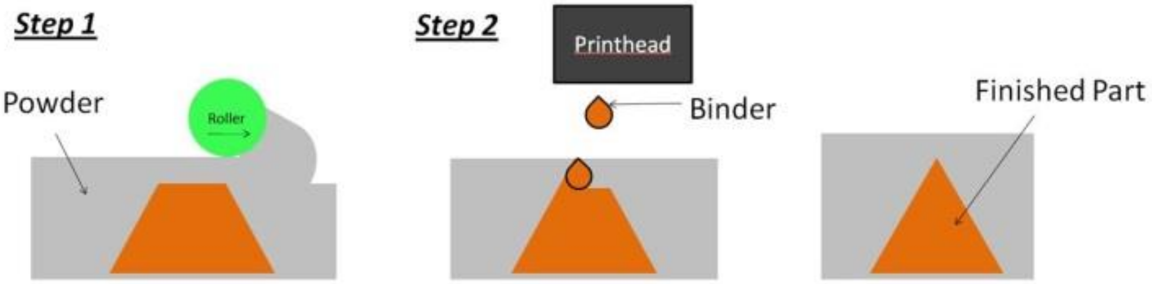

Figure 2. Binder Jetting Printing Process

Research on Binder Jetting patternless sand molds has been conducted and used for many sand casting applications. Kobliska and coauthors (2005) embedded thin film thermocouples in an A356 matrix cast in molds fabricated by ZCorporation printer [7]. Gill & Kaplas (2009) compared castings printed with ZCast® and Investment casting using starch and plaster, including dimensional tolerances, hardness values, surface roughness, production cost, and shrinkage [8]. Additionally, other studies have been conducted in which it was proved cost effective for use of rapid tooling and prototyping [9].

Although the binder jetting process has been used for many applications, including ceramics and powdered metallurgy, much effort has been made for the production and characterization of patternless sand molds. However limited research has been conducted to characterize the binder effects and binder burnout in patternless molds produced by Binder Jetting.

1.2. Effects of Binder in Sand Molds on Castings

It is important to understand the strength comparisons and binder burnout characteristics of printed molds as these properties could greatly affect the final part quality of the castings. For example, Meisel, Williams, and Druschitz were unsuccessful in their initial attempts to cast complex cellular structures using 3D printed molds, due to incomplete filling of the mold at the bottom of the structure [1]. This was caused by gas generation from when binders were exposed to the high temperatures of molten metal. Additional research was conducted by Snelling and coauthors (2012) to mitigate these defects in molds produced by a ZCorporation system. The authors conducted casting data, binder burnout percentages, and total binder content from printed molds [10]. It was concluded the ZCorporation system used large amounts of binder to bind proprietary powders, which resulted in the large amount of off-gassing producing incomplete castings. A curing cycle established to decrease the amount of gas generation while maintaining sufficient strength while increasing the quality of castings. Similar tests have been performed by McKenna et al. (2008) to increase the quality of mold by studying the effects of curing time and temperature on permeability and compressive strength [3]. A mathematical model was used to determine an optimal curing time and temperature for both permeability and compressive strength. It was determined that the best permeability occurred when the molds were baked at 227 °C for 6.2 hours and the best compressive strength at 173 °C for 5.5 hours.

Due to the increased binder requirement for the ZCorporation system and a need for thermal curing cycle studies, the authors look to different technologies to form patternless molds for metal casting. ExOne utilizes a two part binder (furan with binder catalyst) that is similar to chemically bonded molding methods in traditional sand casting applications. This binder selection decreases the amount of binder required to create a mold and therefore eliminates the need for post-processing the printed mold in a thermal curing cycle. There exist no prior literature on the binder burnout and gas generation of ExOne system.

In this work, the ExOne Sand Materialization System will be compared to four different commercially available traditional chemically bonded sand binders on a basis of binder burnout and strength. The characteristics of binder burnout in printed molds enables an understanding of binder burnout percentage at multiple temperatures. This data is then compared to acceptable binder standards and the user is able to select binder type to match casting media (aluminum alloys, iron alloys, steel alloys, etc.).

The experimental methods employed in this work, which are focused in comparing the strength and binder burnout of printed molds against traditional molds, are presented in Section 2. Experimental results are presented in Section 3. Conclusions are offered in Section 4.

2. EXPERIMENTAL METHODS

The purpose of this paper is to provide a comparison of the ExOne Sand Materialization System to traditional binder systems on the basis of strength and binder burnout. This work is guided by the following research question:

Research Question

How does the printed ExOne two part binder system and sand compare with common chemically bonded sand binders?

The ExOne sand material system is compared to four non-printed sands, as listed in Table 1. The sands are compared on the basis of (i) their formed strength and (ii) in the amount of binder burnout. Because chemically bonded sands do not require heat to catalyze a reaction for bonding, two-part polymer binders need to be mixed to create a bond between sand particles. Typically, the binder system consists of a resin and catalyst. There are many resins available including phenolic, furan, alkyds, and sodium silicates, while catalysts include sulfonic acids, isocyanate, and glycerin.

The systems used for comparison were chosen because of they were readily available commercially applied binders and catalysts. The Super Set 942 and TW30 was chosen specifically because of the similarity to the ExOne printed resin system (furan resin and binder catalyst).

Table 1. Printed and Non-Printed Binder Systems for Comparison

Binder System	Printed/Non-Printed	Material Type
ExOne Sand Materialization	Printed	Furan Resin with Binder Catalyst
Alkyd 18-415 and Alkyd 23-217 Coreactant	Non-Printed	Alkyd Resin and Catalyst
Super Set 942 and TW30	Non-Printed	Furan Resin and Acid Catalyst
Chem Bond 490 and Chem Bond 260	Non-Printed	Sodium Silicate Resin with Glycerin Catalyst
Phenoset-RB Part 1 and APR-015 Part 2	Non-Printed	Phenolic Resin with Acetate Ester Catalyst

Because ExOne systems use a furan binder with a binder catalyst, it is expected to have comparable strength and binder burnout of traditional furan and binder catalyst sands, as presented in the Hypothesis.

Research Hypothesis

Printed ExOne sands using furan and binder catalyst will compare to traditional sands that use furan and binder catalysts.

Although the printed sand and chemically bonded sand both use a furan and binder catalyst will compare in strength and binder burnout percentages with time and temperature, they may slightly differ. Printed sands need to be well controlled for accurate placement of binders for increased geometrical accuracy. Because of this need, environmental control including humidity and temperature are kept constant to minimize variability. Additionally, the sand distribution is well controlled (smaller grain size and distribution) which could contribute to differences in properties between the printed and non-printed furan binder systems.

2.1. Production of Specimens for Comparison

In order to compare both printed and non-printed systems, equivalent specimens are needed as a basis for comparison. For evaluation of the sand molds' strength, an AFS standard 3342-00-S tensile specimen is used as the pattern for comparison [11]. Small cubes of the sands were used for evaluating the sands' binder burnout characteristics. Non-printed sand specimens were formed into standard AFS tensile specimens and then cut into small cubes; printed ExOne rectangles were cut into small cubes.

2.1.1. Printed Specimen

Printed specimens were designed in CAD and printed using an ExOne System to the dimensions given by the AFS Standard (Figure 3). A printed specimen can be seen in Figure 4.

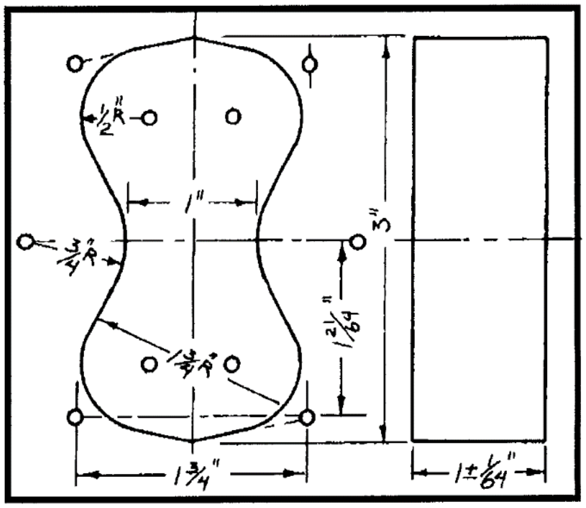

Figure 3. AFS Standard Tensile Specimen AFS 3342-00-S [11]

Figure 4. ExOne Printed AFS Tensile Specimen

2.1.2. Traditional Chemically Bonded Specimens

The sands were combined with each of the binders using a mixer. Sufficient silica sand is used for each binder system in order to fill the AFS 12-gang tensile specimen box. The resin and catalyst are then measured, added, and mixed according to its vendor's recommendations, as showing in Table 2.

Table 2. Binder Systems Used for Comparison for Burnout Characteristics [10,12]

	Binder Addition	Resin/Catalyst	Amount	Addition Order	Mixing Type
1	Alkyd 18-415	Resin	1.5 % by weight of sand	1	Stand Mixer
	Alkyd 23-217 Coreactant	Catalyst	20 % by weight of resin	2	Stand Mixer
2	Super Set 942	Resin	1 % by weight of sand	2	Stand Mixer
	TW30	Catalyst	35 % by weight of resin	1	Stand Mixer
3	Chem Bond 490	Resin	3 % by weight of sand	2	Stand Mixer
	Chem Bond 260	Catalyst	10 % base on weight of resin	1	Stand Mixer
4	Phenoset-RB Part 1	Resin	4:1 Resin to Catalyst; 1.6 % Binder by weight of sand	Simultaneous Mixture	Continuous Sand Mixer
	APR-015 Part 2	Catalyst			

Immediately after mixing the polymer binders with silica sand, the mixture is placed into the AFS standard multi-cavity core box to create the tensile specimens for mechanical and binder burnout tests. An image of the multi-cavity core box can be seen in Figure 5. The tensile specimens are dimensionally equivalent to the printed mold (Figure 3).

Figure 5. AFS Standard Multi-cavity Core Box

2.2. Evaluation of Mechanical Strength of Tensile Specimen

Tensile tests are performed to compare strengths of the traditional binders to the printed ExOne binders. Six specimens were tested for evaluation of strength. All specimens are allowed to cure for a minimum of 24 hours to ensure full polymeric cross-linking. The specimens are tested using the AFS tensile specimen fixture (Figure 4) at room temperature on a Com-Ten 95 Series tensile machine at a rate of 0.6 mm/min – 1.2 mm/min.

2.3. Binder Burnout Characteristics

To evaluate the burnout characteristics of the sand specimens, small pieces of sand bonded with commercially available binders were cut from the remaining tensile specimens (Figure 6). Printed specimens were cut into small cubes from rectangular parts. Each material was separated into small crucibles and an initial weight was taken in order to establish a datum. To maintain consistency, approximately 27 g of each materials was measured in each crucible. One-hour curing cycles were performed for all materials starting at 105°C to remove all humidity. The temperature was then increased to 150°C, to 600°C (via 50°C increments), and then to 900 °C (via 100°C increments); each cycle lasted one hour. After each cycle, the cubes’ mass was evaluated via a balance. The mass was divided by the cubes’ initial mass to determine the percent binder burnout.

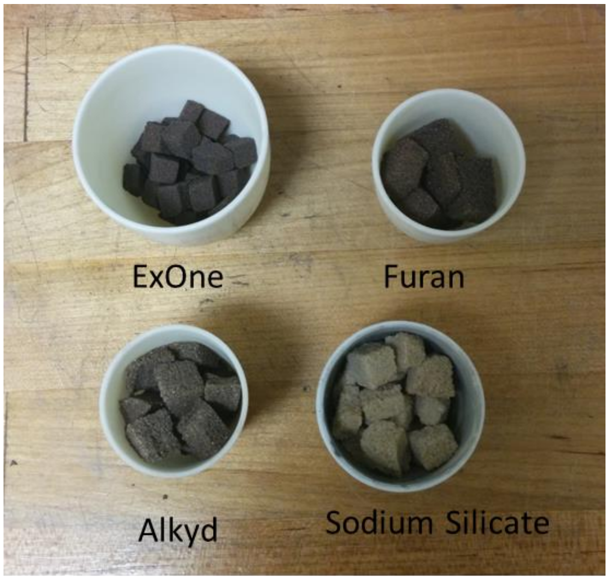

Figure 6. Specimens Used for Binder Burnout Tests

3. RESULTS

3.1. Mechanical Strength

The mechanical strength of the printed and non-printed dogbones, as evaluated by tensile test, are listed in Table 3.

Table 3. Results of Strength Tests of both Printed and Non-Printed AFS Dogbones

Binder Type	Mean Strength (kPa)	Standard Deviation (kPa)
ExOne – Printed	1324.931	168.2576
Alkyd 18-415 and Alkyd 23-217 Coreactant	964.901	83.6231
Super Set 942 and TW30	397.028	46.2907
Chem Bond 490 and Chem Bond 260	128.511	20.6333
Phenoset-RB Part 1 and APR-015 Part 2	561.509 [10]	92.5800 [10]

From the results, the ExOne printed tensile specimens are significantly stronger than the non-printed binder systems. The combination of furan binder and binder catalyst and refined sand distribution provide enhanced strength over the common phenolic binders (Phenoset resin and APR catalyst).

It was hypothesized that the furan resin with binder catalyst (Super Set 942 and TW30) would have similar characteristics to the printed specimens because they used a similar two part system with minor changes in properties due to better control of sand distributions in the ExOne system. However, this factor exhibits a larger effect than first hypothesized. The ExOne printed specimens maintain sufficient strength for handling and casting alloys.

3.2. Binder Burnout Characteristics

In order to equally compare binder burnout characteristics, the values for burnout are normalized. This results in a percentage of burnout at each temperature up to 900 °C. The normalized percentage loss is illustrated in Figure 7.

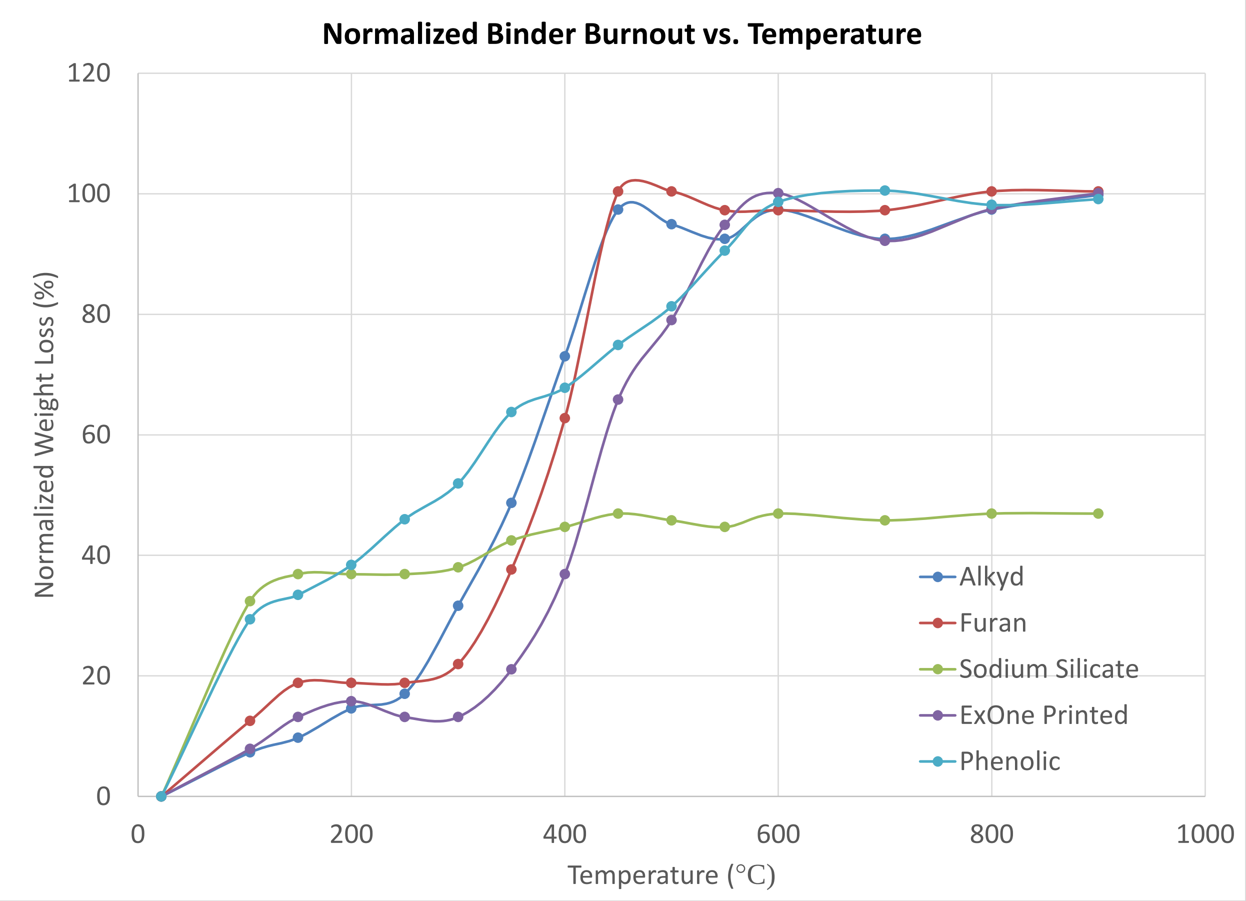

Figure 7. Weight Loss Comparison of Printed and Non-printed Chemically Bonded Sands

From the results of the weight loss comparison, there are significant differences in the binder burnout characteristics of all binders in both printed and non-printed systems. For all binders, there is a large jump in burnout at the initial temperature of 105 °C due to the loss in moisture trapped in the specimens. The Chem Bond 490 and Chem Bond 260, as well as Phenoset-RB and APR-015, plateau after the initial loss in moisture. Each binder system contains a temperature where they begin to rapidly decrease in binder content. These are illustrated in Table 4.

Table 4. Temperature of Increased Rate of Binder Burnout

Binder System	Increased Rate of Binder Burnout
ExOne – Printed	300 °C
Alkyd 18-415 and Alkyd 23-217 Coreactant	250 °C
Super Set 942 and TW30	300 °C
Chem Bond 490 and Chem Bond 260	450 °C
Phenoset-RB Part 1 and APR-015 Part 2 [10]	150 °C

Both the values of temperature for increased rate of burnout and values at maximum burnout are important to understanding which binder systems are suited for ranges metal alloy. For example, binder burnout at a lower temperature may be more applicable for alloys with lower melting points. Although the binders may burnout at a lower temperature, they may have more desirable features such as lower health hazard, minimal binder requirement, lower cure time, decreased strip time, etc.

As discussed in Section 1.1, more binder present increased off-gassing when molten metal comes in contact with the mold, therefore a decrease in quality of the final part. Figure 8 illustrates the weight loss percentage versus temperature. Although all of the specimens completely burnout binder content, the ExOne printed specimens show a binder burnout at much higher temperatures as compared to the other binder systems. This will result in increased quality as compared to other non-printed binder systems (Alkyd 18-415 and Alkyd 23-217 Coreactant, Super Set 942 and TW30, Chem Bond 490 and Chem Bond 260, and Phenoset-RB Part 1 and APR-015 Part 2) as well as other studied printed binder systems for patternless molds (ZCorporation [10]).

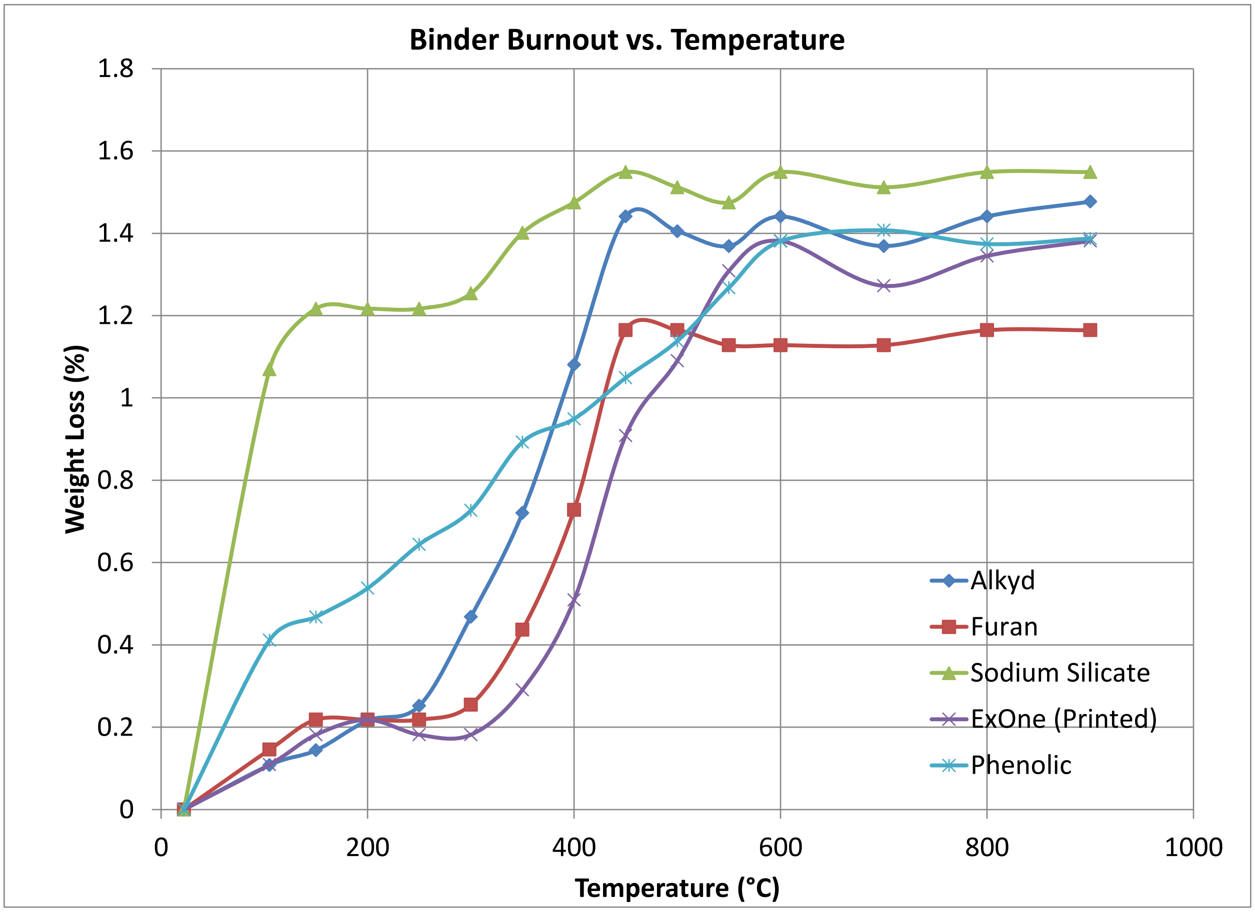

Figure 8. Total Binder Burnout Weight Loss of Printed and Non-Printed Systems

Additionally, it was hypothesized that the printed ExOne binder system would behave similar to that of the Super Set 942 and TW30 as both are furan and binder catalyst systems. From Figure 7 and Figure 8, both the ExOne and Super Set 942 and TW30 binder systems follow a similar trend as expected. However, printed molds held shape at higher temperatures when compared those of the traditional furan (Super Set 942 and TW30) system. Figure 9 illustrates both the ExOne printed mold and Super Set 942 and TW30 systems after binder burnout at 450 °C.

Figure 9. a) Printed ExOne Mold and b) Super Set 942 and TW30 after Binder Burnout at 450 °C

4. CONCLUSIONS

The purpose of this paper is to compare specimens on the basis of strength and binder burnout from both printed and non-printed molding techniques. ExOne Sand Materialization System is compared to four commonly used chemically bonded binder systems as a basis for comparison. Understanding these characteristics of printed molds are of increased importance due to the potential defects from large amounts of binder causing excessive amounts of gas in castings. Binder gives strength to the part to maintain structurally sound mold for handling and decrease erosion from molten metal, but consequently generates large amounts of gas producing defects.

It was hypothesized that the ExOne specimens would have similar characteristics to the Super Set system as both are furan resin and binder catalyst systems. However, the strength was significantly higher for the ExOne printed sands due the well-controlled sand and binder distributions. The ExOne printed tensile specimens were also much significantly stronger than all other commercially available binder systems tested Table 3. The printed specimens were followed similar trends (Figure 7 and Figure 8) in the binder burnout percentages at temperature to the Super Set 942 and TW30, although the ExOne specimens maintained shape longer (Figure 9). The ExOne specimens also had a higher burnout temperature as compared to the remaining binder systems.

Overall, when compared to traditional sand, the printed binder system had superior mechanical performance and contained low binder content for gas generation while maintaining its shape at higher temperatures.

5. REFERENCES

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