CERP
Casting Emission Reduction Program

Prepared by:
TECHNIKON LLC
5301 Price Avenue ▼ McClellan, CA, 95652 ▼ (916) 929-8001
www.technikonllc.com

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Digital Sand Core Manufacturing Study

Technikon #1410-131

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EPA United States Environmental Protection Agency
CISA
AFS AMERICAN FOUNDRY SOCIETY, INC.
UNITED STATES COUNCIL FOR AUTOMOTIVE RESEARCH
USCAR
DAIMLERCHRYSLER Ford Motor Company General Motors

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Technikon # 1410-131

This report has been reviewed for completeness and accuracy and approved for release by the following:

Prepared by: *// Original Signed //* ______
Kevin Langel Date

Process Engineering Manager: *// Original Signed //* ______
Steven Knight Date

VP Measurement Technologies: *// Original Signed //* ______
Clifford Glowacki, CIH Date

VP Operations: *// Original Signed //* ______
George Crandell Date

President: *// Original Signed //* ______
William Walden Date

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Executive Summary

This report covers a process development effort to digitally manufacture sand cores with Three Dimensional Printing (3DP), a technology pioneered by Soligen, Inc. This process is similar to stereo-lithography in which the printing process uses a binder system printed onto a sand bed.

The advantage of Digital Core Manufacturing (DCM) from the environmental aspect includes near zero air emissions, less energy usage and elimination of core making emission control equipment. Additionally, the process eliminates the requirement for conventional foundry tooling (core boxes, patterns, etc.). A CAD file of a part can be directly converted and programmed into a 3DP printer resulting in a cast finished part in days versus waiting months for hard tooling. The disadvantage that needs to be overcome is that printed core making is slower than conventional core blowing.

The binder selected for testing was a protein based binder system supplied by Hormel Foods, activated with water. This material, trade name GMBond®, had previously been tested at Technikon and was the lowest emission core binder tested to date. Multiple equipment and process problems were successfully overcome to use GMBond® in this process for making cores.

The core printing process resulted in multiple core shapes being made successfully. Tensile testing of printed dogbone cores proved that the 3D printing process was capable of making cores that equaled the strength of conventional core blowing. Additionally, testing at Soligen has shown that simple test castings can be made with digitally manufactured sand cores in aluminum. Further development is planned to increase the productivity of the process and to make improvements in casting quality.

It must be noted that the reference and product testing data referenced in this report is not suitable for use as emission factors or for purposes other than evaluating the <u>relative emission</u> reductions associated with the use of alternative materials, equipment, or processes. The emissions measurements are unique to the specific castings produced, materials used, and testing methodology associated with these tests, and should not be used as the basis for estimating emissions from actual commercial foundry applications.

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1.0 Introduction

1.1 BACKGROUND

Technikon LLC is a privately held contract research organization located in McClellan, California, a suburb of Sacramento. Technikon offers emissions research services to industrial and government clients specializing in the metal casting and mobile emissions areas. Technikon operates the Casting Emission Reduction Program (CERP). CERP is a cooperative initiative between the Department of Defense (US Army) and the United States Council for Automotive Research (USCAR). Its purpose is to evaluate alternative casting materials and processes that are designed to reduce air emissions and/or produce more efficient casting processes.

This report covers a process development effort to digitally manufacture sand cores with Three Dimensional Printing (3DP), a technology pioneered by Soligen, Inc. Soligen obtained a worldwide (initially exclusive and currently non-exclusive) license to Three Dimensional Printing (3DP), a technology invented and patented by the Massachusetts Institute of Technology, for the metal casting field. This MIT technology remains the basis for the Company's current DSPC® (Direct Shell Production Casting) technology. The focus of current research and development activities at Soligen is geared toward the printing of intricate cores in production quantities, to replace conventionally produced cores in casting lines for cylinder heads and engine blocks. Digital Core Manufacturing (DCM) promises to revolutionize foundries that produce high-value castings like cylinder heads and engine blocks by greatly reducing lead times, corebox tooling, and by allowing parts to be cast with superior mechanical properties and intricate features.

1.2 CERP OBJECTIVES

The primary objective of CERP is to evaluate materials, equipment, and processes used in the production of metal castings. Technikon's facility was designed to evaluate alternate materials and production processes designed to achieve significant air emission reductions, especially for the 1990 Clean Air Act Amendment. The facility has a Research Foundry designed to measure airborne emissions from individually poured molds. Technikon's operation has been specially designed to facilitate the collection and evaluation of airborne emissions and associated process data. The data collected during the various testing projects are evaluated to determine both the airborne emissions impact of the materials and/or process changes, and their stability and impact upon the quality and economics of casting and core manufacture. The materials, equipment, and processes may need to be further adapted and defined so that they will integrate into current casting facilities smoothly and with minimum capital expenditure.

Normally, Pre-Production testing is conducted in order to evaluate the air emissions impact of a proposed alternative material, equipment, or process in the most cost effective manner. The Pre-Production Foundry is a simple general purpose manual foundry that was adapted and instrumented to make detailed emission measurements using methods based on EPA protocols for pouring, casting cooling, and shakeout processes on <u>discrete</u> molds under tightly controlled conditions not practical in a commercial foundry.

It must be noted that the results from the reference and product testing performed are not suitable for use as emission factors or for other purposes other than evaluating the relative emission reductions associated with the use of alternative materials, equipment, or manufacturing processes. The emissions measurements are unique to the specific castings produced, materials used, and testing methodology associated with these tests. These measurements should not be used as the basis for estimating emissions from actual commercial foundry applications.

1.3 REPORT ORGANIZATION

This report has been designed to document the results to date of ongoing research and development activities involved in the adaptation of Soligen DSPC (Direct Shell Production Casting) machines for building sand cores. An overview of the process will be presented along with a discussion of the problems and successes to date.

2.0 Digital Core Manufacturing Process Testing Methodology

2.1 THEORY OF OPERATION

The production of a mold or core on the DSPC machine is accomplished through a layer by layer printing process. Prior to a build, the machine operator spreads a base layer of dry, coated sand in the build box. The machine's software slices through a stereo lithography (STL) file at user-specified intervals effectively converting a three-dimensional file into many stacked two-dimensional slices. These 2D slices reveal location information about where and where not, to print.

Figure 2.1.1 is a diagram of the current Digital Core Manufacturing process using Soligen's equipment and Figure 2.1.2. is a typical Mold and Core Package from the process.

Figure 2.1.1 DCM Process

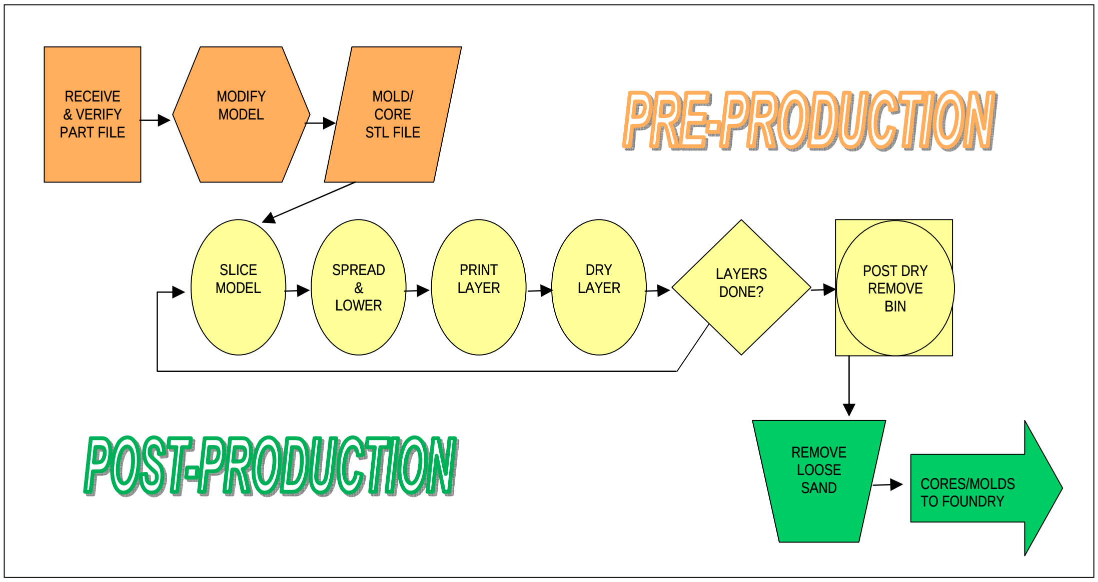


Figure 2.1.2 Typical Mold and Core Package

Figure 2.1.3 Printing Machine

Soligen DSPC machine

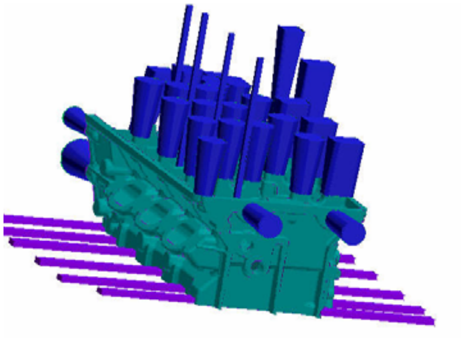
As the print head travels to its starting position, the machine spreads a fine layer of sand, rolling it smooth as it goes. (Figure 2.1.3) The machine then lowers the build box by a small increment (the slice height), and begins to print a precise cross-section of the current layer with an aqueous solution on the sand. The printed area is subsequently dried, and the areas of the build box that are hydrated and dehydrated will bond together. After traversing the length of the build box, the machine slices the STL file again. This sequence of slicing, spreading, lowering, printing, and drying is repeated many times to build up a mold or core component.

The results within the build box are regions of bound and unbound sand, in the physical form of molds or cores, surrounded by a supportive margin of unbound sand.

2.2 COMPUTER MODEL PREPARATION

The pre-production side of DCM involves all the file verification and preparation upstream of the actual production. Modifications specific to the process must be done to the part model to ensure successful casting, and a CAD designer familiar with designing for the DSPC machines must verify the end products. Upon receiving a solid model (CAD file) from the customer, several operations must be performed by a DCM specialist before uploading files to the DSPC machine. The file modifications vary depending on what is to be built (see Figure 2.1.4). If an entire mold is to be made the following must be done:

Figure 2.1.4 Part Model



Part model with risers and vents

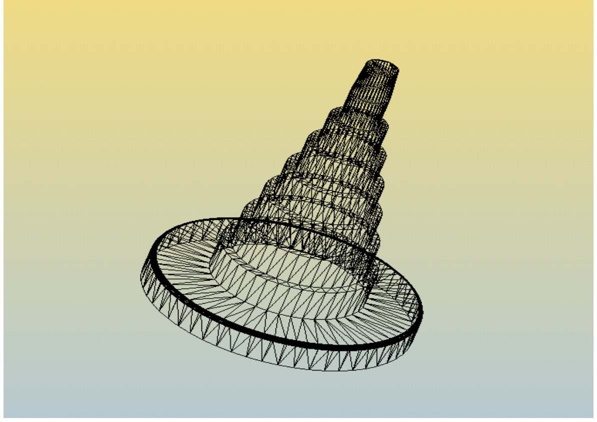
1. Part model dimensional adjustment to compensate for shrinkage.
2. Extra stock is added for machined surfaces.
3. Construct gating and riser system to feed cavity.
4. Add chills and vents as necessary.
5. Build a mold model, driven by the modified part model geometry.
6. Sectioning the mold model allows molds larger than the machine build envelope to be made.
7. Allow mold to be split, to remove unbonded sand after printing.

If cores only are to be made, the following must be done:

1. Part model dimensional adjustment to compensate for shrinkage.
2. Build a core model driven by part model geometry.
3. Geometry may need to be added to locate core in mold.
4. Add simple support structures for delicate cores.
5. Package multiple cores to take full advantage of the machine's build envelope.

The mold or core model will thus be a model of the "negative" area, or the air space in and/or around the customer's original part model. These mold or core models are converted into a stereo lithography, or STL file, commonly used in rapid prototyping machines (see Figure 2.1.5). This file contains a description of the surface of a solid that has been decomposed into triangles. It is this STL file that is uploaded to the machine via Ethernet, and provides the geometric information the machine requires.

Figure 2.1.5 STL File



Stereo lithography (STL) file

2.3 TESTING METHOD

Technikon does not have the equipment necessary to execute DCM in house. Therefore a plan was developed to test sand based resin systems by utilizing existing equipment located at Soligen's facilities in Southern California. Technikon engineers accomplished the testing under the supervision of Soligen technicians.

Hormel participated by supplying various batches of GMBond® sands coated with different formulations of protein binder for testing at Soligen.

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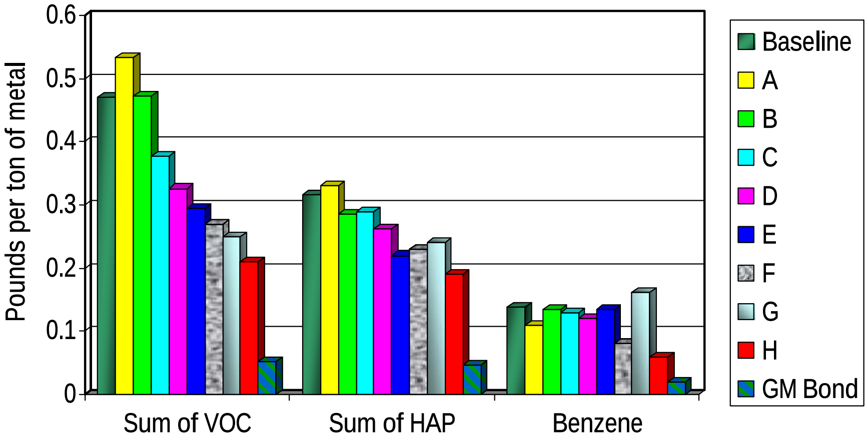
3.0 Material Development and Preliminary Build Experiment Results

3.1 CORE BINDER SYSTEM SELECTED FOR TESTING

The goal of this process development project was to find a low emission binder system that would work as a printing binder for DCM. When developing a materials system for building sand cores on the DSPC machines, there were several areas to consider, including safety, cost, and foundry compatibility. Our first choice for testing was a protein binder system sold by Hormel Foods named GMBond®. This binder system has demonstrated lower emissions in the form of hazardous air pollutants (HAPs) and volatile organic compounds (VOCs) than traditional phenolic resin core binders. See Figure 3.1.1 for emission comparisons from CERP testing

Figure 3.1.1 Pouring, Cooling and Shakeout Emissions of GMBond® Compared to Other Binder Systems.



The mold or core base material and binder used in DCM had to be economically practical as well. At Soligen, DSPC machines have been making ceramic molds for over a decade, but their binder/ powder system is costly and requires stringent controls to maintain the proper consistency. It would not be cost-effective for production runs in the tens to hundreds of castings range. The GMBond® system of factory pre-coated sand may be used in DCM machines as well as conventional core blowing equipment. Thus a foundry already running GMBond® seeking to augment their core blowing capabilities with DCM, would not have to invest in an exotic material system.

The driving factor in developing a material system for DCM, however, is to make it “foundry friendly.” This means that the build media used must have:

- Compatibility with existing foundry sand systems.
- Acceptable scratch hardness and tensile strengths.
- Acceptable casting quality
- Acceptable shakeout characteristics.
- Ability to reclaim cores without using thermal processes.

The GMBond® system may be used to coat a variety of sands with different grain shape and fineness. Our Experiments have been conducted using Michigan “lake sand” as well as an Oklahoma silica sand, both well known by U.S. foundries. Further development will be needed to determine optimal binder levels in the pre-coated sand for different grain sizes, and determine what kind of resolution and surface finish can be expected from cores or molds when using the different types of sand. An advantage of GMBond® is that the print head is printing with water therefore no harmful chemicals are being used during the process.

Print head settings, binder levels and the hydration/dehydration cycle ultimately determine factors like scratch hardness and tensile strength in a mold or core built with DCM. Further testing is planned to optimize these build parameters. See appendix A for an example of the DCM evaluation form used when preparing a new build.

An advantage in using GMBond® for cores is that aggressive shakeout and shot blast cycles are not necessary with aluminum castings. If stuck-on core pieces persist after shakeout, they may be removed with a water spray. In greensand foundries, core sand inevitably makes its way into system sand. GMBond® cores break down in a muller and assimilate well in this respect, whereas some core materials resist mulling or introduce unwanted compounds into a greensand system, making it difficult for the sand lab to determine mold strength, clay concentrations, etc.

3.2 CORE SHAPES SELECTED FOR TESTING

To test core printing and to analyze process properties a few basic core designs were developed in CAD and downloaded to a test machine at Soligen. The core shapes selected included:

- Standard AFS Dogbone tensile test specimens – purpose was to determine strength of binder bonding (see Figure 3.2.1)
- Enclosed Rectangular Box – purpose was to observe static clinging and binder bleed out issues (see Figure 3.2.2)
- Cylinder Head Port Core - as a demonstration of an actual core that would be used in production (see Figure 3.2.3)

Figure 3.2.1 Dogbone Cores in As-Printed and After Removal

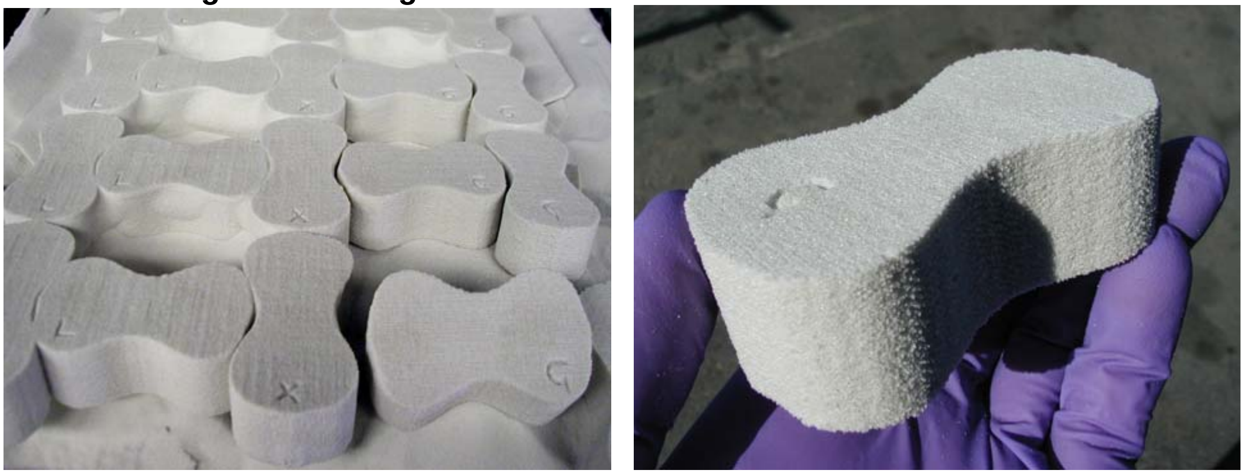


Figure 3.2.2 Rectangular Box Cores

Showing the effect of increasing air flow on completeness

3.3 PROCESS DEVELOPMENT AND TESTING

Testing plans for GMBond® were completed in September 2003, and Testing Cycles were done at Soligen starting in October and continued till mid May of '04.

Over the testing period, various sand types and sand grain sizes were tested. The first sand was a 55 grain fineness number (GFN) lake sand which proved to be too coarse for a good surface finish. The 2nd sand was a fine alumina powder that Soligen uses in their ceramic mold process; this proved to be too fine and created weak cores. The 3rd sand was an Oklahoma Silica - 90 GFN (OK90); which showed the best results.

Figure 3.2.3 Cylinder Head Port Cores in Print Box Done with Lakesand

Hormel also supplied sands with different protein coating methods (liquid coated and gel coated). There proved to be a good correlation on the coating type on the sand to core strength. The results of these variations were demonstrated in tensile testing and are displayed in Figure 3.3.1. These tensile strengths are equal or better than normally seen in blown cores used successfully every day. (Typical ColdBox® Cores range between 200 to 300 psi tensile strength, depending on binder level.)

Figure 3.3.1 Tensile Strength Results

Samples of OK90 (liquid)	Sample Weight (gms)	Tensile Strength (psi)	Strain Elongation (in/in)
Average	98.1	317.4	0.090
Std Dev.	1.7	83.6	0.015
Range	5.6	269.9	0.048

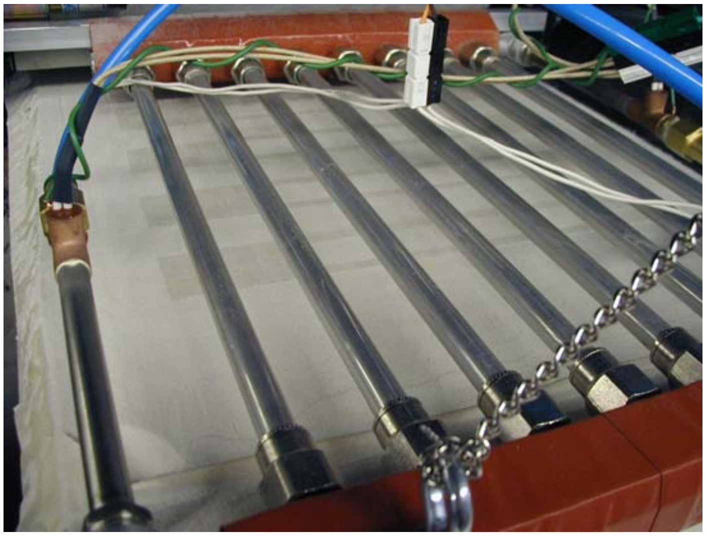
Samples of OK90 (gel)	Sample Weight (gms)	Tensile Strength (psi)	Strain Elongation (in/in)
Average	97.2	268.5	0.086
Std Dev.	0.8	92.6	0.017
Range	2.3	258.0	0.053

3.4 PROCESS PROBLEMS IDENTIFIED DURING DEVELOPMENT AND TESTING

The major problems experienced during the testing period were getting the correct amount of water on the sand and then drying the layer in a reasonable cycle time. If this wasn't accomplished, delamination and layer curling resulted. Various drying methods were investigated including; heat lamps, heated sand, and heated air. An electrically heated blower manifold was designed that was somewhat successful (see figure 3.4.1). Further development in this area is planned to improve the drying time.

Another problem that still needs resolution is elimination of static charge buildup related to spraying water on coated GMBond® sand. This results in sand attaching itself to the print head. The solution to the static charge may lay in improved grounding of the sand bed which should be solvable.

Figure 3.4.1 Showing Heated Air Manifold Over Sand Bed



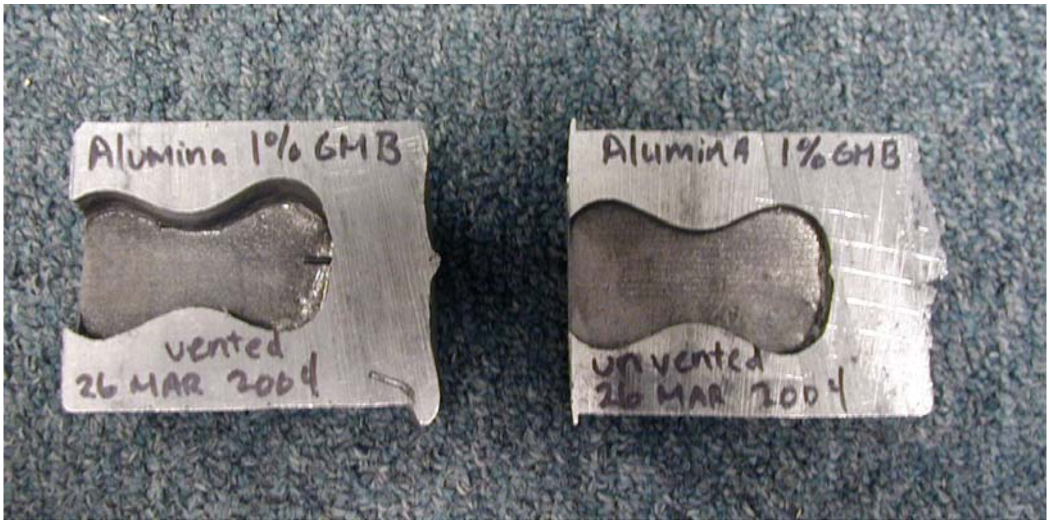
Drying test geometry

3.5 CASTING RESULTS

Test castings were made with Alumina powder Dogbones as internal cores poured with Aluminum. An open topped riser sleeve was used as the mold. See Figure 3.5.1 for mold arrangement and Figure 3.5.2 for sections through dogbone core and finished casting.

Figure 3.5.1 Poured Molds

Figure 3.5.2 Sections of Castings



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4.0 Discussion of Results and Future Testing of DCM Technology

4.1 PRESENT STATUS

Testing at Soligen has shown that simple test castings can be made with digitally manufactured sand cores in aluminum. Multiple equipment and process problems have been overcome to use GMBond® successfully for the test cores and parts made. Tensile testing of dogbone cores proved that the 3D printing process was capable of making cores that equaled the strength of conventional core blowing. See Appendix B for tensile testing results.

The process using sand as the print media is not production ready and refinements are necessary to develop a robust process that would be considered ready for commercialization. In the 2004 Army contract, development will be continued and more complex cores and castings will be attempted. Machine redesign for sand core systems will also be started.

4.2 ULTIMATE GOAL FOR PROCESS

Complex, highly cored castings done in limited production such as specialty automotive manifolds and cylinder heads would be well suited for a digitally manufactured cores and molds. Also DoD short run casting requirements could best be met with DCM when tooling does not exist. The use of DCM to produce complex cores and molds would eliminate the need for traditional patterns and core boxes. Additionally casting changes can easily be made without revisions to core boxes. With conventional core blowing, a new set of tooling must be produced to accommodate every change a design engineer makes to core geometry. Changes can be made to cores produced via DCM simply by modifying the solid models and uploading a new file to the machine; there is much less lead time and no tooling expense involved.

CERP's goal is to bring this process into the mainstream utilizing environmentally benign binder systems. This would solve DoD need for low production castings and the industries need for an inexpensive short run production method.

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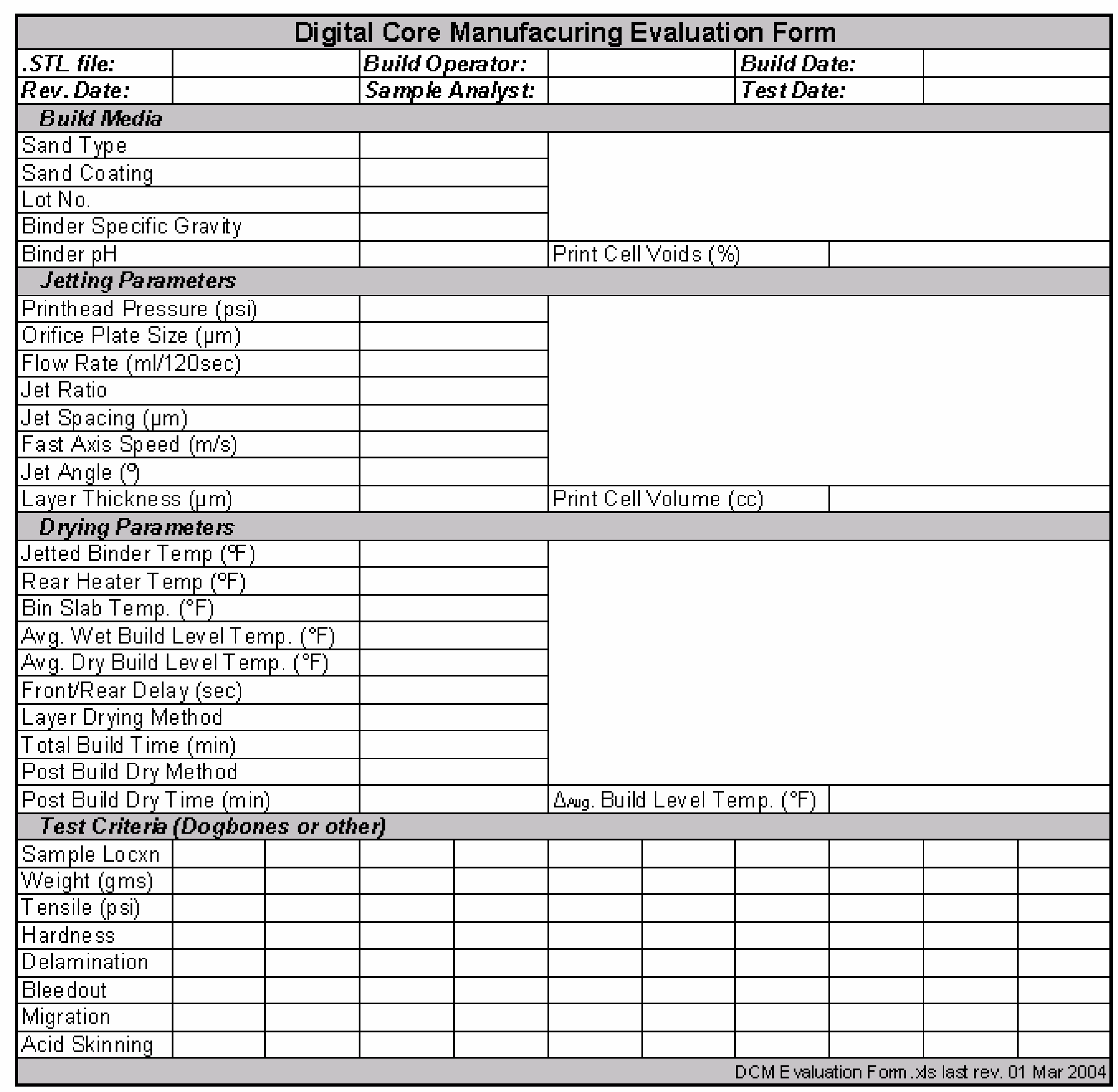
APPENDIX A DCM BUILD LOG & EVALUATION FORM



Digital Core Manufacuring Evaluation Form

.STL file:		***Build Operator:***		***Build Date:***	
Rev. Date:		***Sample Analyst:***		***Test Date:***	

Build Media

Sand Type			
Sand Coating			
Lot No.			
Binder Specific Gravity			
Binder pH		Print Cell Voids (%)	

Jetting Parameters

Printhead Pressure (psi)			
Orifice Plate Size (µm)			
Flow Rate (ml/120sec)			
Jet Ratio			
Jet Spacing (µm)			
Fast Axis Speed (m/s)			
Jet Angle (°)			
Layer Thickness (µm)		Print Cell Volume (cc)	

Drying Parameters

Jetted Binder Temp (°F)			
Rear Heater Temp (°F)			
Bin Slab Temp. (°F)			
Avg. Wet Build Level Temp. (°F)			
Avg. Dry Build Level Temp. (°F)			
Front/Rear Delay (sec)			
Layer Drying Method			
Total Build Time (min)			
Post Build Dry Method			
Post Build Dry Time (min)		$\Delta_{Aug.}$ Build Level Temp. (°F)	

Test Criteria (Dogbones or other)

Sample Locxn										
Weight (gms)										
Tensile (psi)										
Hardness										
Delamination										
Bleedout										
Migration										
Acid Skinning										

DCM Evaluation Form.xls last rev. 01 Mar 2004

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APPENDIX B TENSILE TEST RESULTS

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TECHNIKON

SAND LAB DATA SHEET

Applicable AFS Test Specs: *[T-A tensile tester used]*

Sample Build Date	Sample Test Date	Build Orientation (X or Y)	Sample Weight (gms)	Tensile Strength (psi)	Strain Elongation (in/in)	Notes
5/12/2004	6/3/2004	Y	99.6	155.2	0.058	OK90 dried from liquid
5/12/2004	6/3/2004	X	100.2	375.8	0.095	OK90 dried from liquid
5/12/2004	6/3/2004	Y	99.1	257.3	0.085	OK90 dried from liquid
5/12/2004	6/3/2004	X	99.6	388.4	0.106	OK90 dried from liquid
5/12/2004	6/3/2004	X	96.8	405.4	0.106	OK90 dried from liquid
5/12/2004	6/3/2004	Y	97.5	215.5	0.079	OK90 dried from liquid
5/12/2004	6/3/2004	X	97.2	404.5	0.117	OK90 dried from gel
5/12/2004	6/3/2004	Y	97.0	156.3	0.069	OK90 dried from gel
5/12/2004	6/3/2004	X	98.3	341.8	0.106	OK90 dried from gel
5/12/2004	6/3/2004	Y	98.3	167.1	0.074	OK90 dried from gel
5/12/2004	6/3/2004	X	97.7	318.8	0.095	OK90 dried from gel
5/12/2004	6/3/2004	Y	98.0	146.5	0.074	OK90 dried from gel
5/13/2004	6/3/2004	Y	98.8	259.2	0.090	OK90 dried from liquid
5/13/2004	6/3/2004	Y	97.1	367.0	0.090	OK90 dried from liquid
5/13/2004	6/3/2004	X	99.4	334.3	0.095	OK90 dried from liquid
5/13/2004	6/3/2004	X	98.3	348.9	0.106	OK90 dried from liquid
5/13/2004	6/3/2004	Y	96.1	277.1	0.074	OK90 dried from liquid
5/13/2004	6/3/2004	X	94.6	425.1	0.100	OK90 dried from liquid
5/13/2004	6/3/2004	Y	96.5	206.1	0.069	OK90 dried from gel
5/13/2004	6/3/2004	X	96.0	370.0	0.100	OK90 dried from gel
5/13/2004	6/3/2004	X	97.0	320.8	0.090	OK90 dried from gel
5/13/2004	6/3/2004	X	97.1	349.9	0.095	OK90 dried from gel
5/13/2004	6/3/2004	Y	96.1	188.8	0.064	OK90 dried from gel
5/13/2004	6/3/2004	Y	97.2	251.0	0.074	OK90 dried from gel
		Average	**97.6**	**293.0**	**0.088**	
		Std Dev.	**1.4**	**89.8**	**0.016**	
		Max value	**100.2**	**425.1**	**0.117**	
		Min Value	**94.6**	**146.5**	**0.058**	

Samples of OK90 (liquid)	Sample Weight (gms)	Tensile Strength (psi)	Strain Elongation (in/in)	Notes
Average	**98.1**	**317.4**	**0.090**	**18% improvement in UTS over gel samples**
Std Dev.	**1.7**	**83.6**	**0.015**	
Max value	**100.2**	**425.1**	**0.106**	
Min Value	**94.6**	**155.2**	**0.058**	

Samples of OK90 (gel)	Sample Weight (gms)	Tensile Strength (psi)	Strain Elongation (in/in)	Notes
Average	**97.2**	**268.5**	**0.086**	
Std Dev.	**0.8**	**92.6**	**0.017**	
Max value	**98.3**	**404.5**	**0.117**	
Min Value	**96.0**	**146.5**	**0.064**	

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APPENDIX C GLOSSARY

3DP	Three Dimensional Printing
DCM	Digital Core Manufacturing
CAD	Computer Aided Design
DSPC	Digital Shell Production Castings
STL	Stereo lithography
DoD	Department of Defense