CERP
Casting Emission Reduction Program

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Permanent Mold Technology

Technikon # 1410-160

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

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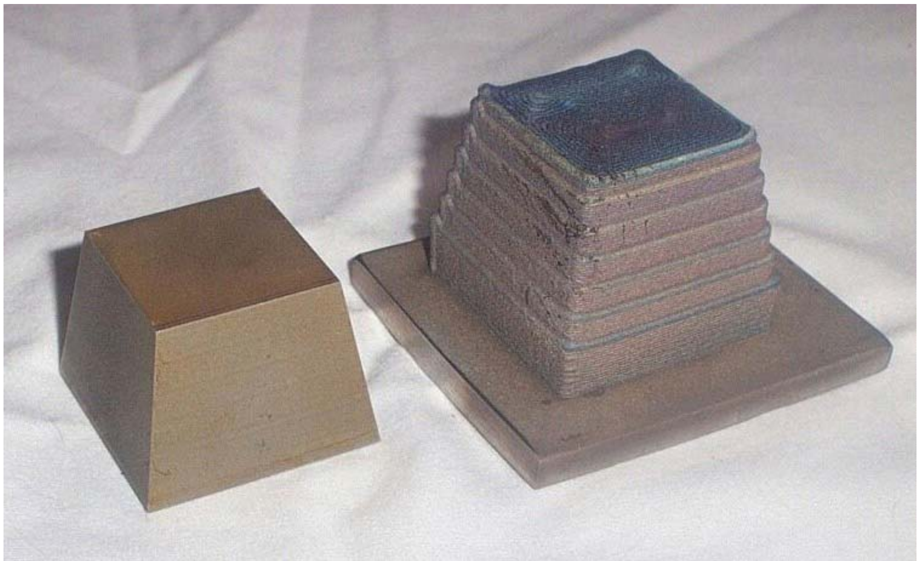
Executive Summary

CERP's goal is to find processes that reduce air emissions. Permanent mold technology is common for lower melting temperature metals (such as aluminum), but not common with higher melting temperature metals (such as iron). The Army Research Laboratory (ARL) and CERP selected materials to test that might be good candidates for iron permanent molds.

This report covers the process methodology used to select candidate alloys for evaluation as a high temperature permanent mold insert material. The results of the manufacturing of the test die blocks/coupons by a process known as laser consolidated powder deposition for each of the candidate alloys is discussed in this report. Figure 1 shows a laser consolidated durability block on the right and machined block on the left that will be used in mold tests. A phase 2 study is planned to pour cast shapes in molds and look at the effects of temperature on four different alloys.

Figure 1 H13 Durability Blocks – Machined and Laser Consolidated



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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 metal casting and emissions measurement technology. 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 development work between CERP and the U.S. Army Research Laboratory on a joint three-phase program to develop an economically feasible permanent mold system for high-temperature castings that would replace sand molds. The cost of sand purchase and disposal is described in Appendix A.

Spent molding sand from metal casting operations is by far the largest waste stream from a given foundry. Approximately 800 pounds of waste sand is generated in the production of one ton of ferrous castings. Additionally, 350 pounds of slag and 200 pounds of airborne dust are generated per ton of castings. The estimated national cost for the operation of pollution abatement equipment in this industry is $1.25 billion per year. The landfill tipping fee for disposal of these waste streams is $25 to $100/ton for non-hazardous and up to $350/ton for hazardous waste.

Clearly, the exercise of pollution prevention techniques in the casting operation can yield significant cost savings. In the sand casting process, the cavity in the sand mold is formed by packing sand around a pattern and then removing the pattern by separating the mold into two halves. The mold is closed, without the pattern, and molten metal is then poured into the cavity. When the metal has solidified and cooled the sand is removed. There are many variations of this method, including shell molding, vacuum molding and investment casting. These methods differ in manufacture time and waste streams, but they all use an expendable mold. One approach which eliminates a sand waste stream entirely is the use of a permanent metal mold.

A permanent mold is one that is not destroyed in a single casting process but can be used to make many castings. The permanent mold is often composed of iron for aluminum, copper, magnesium, and zinc alloys and is constructed in two halves. The term “permanent mold” is somewhat misleading, since the molds will not last forever. The service life of a permanent mold is dependent on the complexity of the part, the mold material used, and the alloy being cast.

The mold interior is coated with a graphite refractory which acts as a thermal barrier and as a parting agent. The mold halves are mated and preheated to about 300-400°F. Low melting point molten metal is poured into the mold. Water channels or heat sink fins are used to cool the mold quickly. The cooled casting is removed and the mold reused. No waste sand is generated in this process.

Permanent molds may have metal or sand cores. A semi-permanent mold is a permanent mold in which sand cores are used, and the cores are destroyed in the casting process. Permanent mold casting is sometimes referred to as "gravity die casting", since the metal is poured under gravity without external pressure being applied. It may also be called "chill casting", because the materials used for the mold rapidly cools the casting.

A permanent mold may have a number of cores, depending on the design of the component to be cast. Gates and risers are designed to minimize turbulence during pouring and provide reservoirs of molten metal that reduce the risk of shrinkage and porosity. Once solidification has occurred, the casting is removed from the mold by ejector pins or by retraction of movable cores.

Although permanent molds are more expensive than sand molds, the process offers a number of advantages, including higher production per unit time per unit of equipment, improved mechanical properties, finer grain size, smooth surface finish, closer dimensional tolerances and lower machining costs.

Permanent mold casting ranks second to sand casting in popularity. However, the tonnage produced by the process is only a small percentage of that made by sand casting. About 500-units is generally considered to be the minimum number of castings for which a permanent mold may be built economically.

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 is designed to evaluate alternate materials and production processes designed to achieve significant air emission reductions. 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.

The increased utilization of permanent molds would reduce the air emissions associated with the normal sand binder systems. This would meet the objectives of the Casting Emission Reduction Program of developing new processes that reduce air emissions.

1.3 REPORT ORGANIZATION

This report has been designed to document the results to date of ARL in making test coupons that would be used to determining better materials for permanent molds. It also discusses the next phase of testing planned.

1.4 SPECIFIC TEST PLAN AND OBJECTIVES

The principal drawback to the application of permanent molds to the casting of higher temperature metals such as iron, steel, nickel, and titanium is a short mold lifetime. This shortened lifetime is caused by thermal shock when molten metal is poured, as well as wear produced in the removal of previously used mold coatings. This durability problem is the reason for marginal use of permanent molds for alloys with melting temperatures greater than 2200ºF.

A test method has been formulated that is designed to characterize the resistance to thermal cracking of the mold materials that will be evaluated. Characterization of thermal fatigue or cracking best predicts a successful permanent mold. This characterization can be accomplished through contact with the liquid metals to be cast. Durability blocks of candidate mold materials will be inserted into a 2 x 2 durability mold that will hold four durability blocks for evaluation per casting trial. This will be done repeatedly and the durability blocks inspected for cracking and soldering (wear of edges and corners) between pours. Initially iron will be poured. This method requires the fabrication of durability blocks (see Figure 2) of each mold material selected for evaluation.

Figure 2 Durability Block

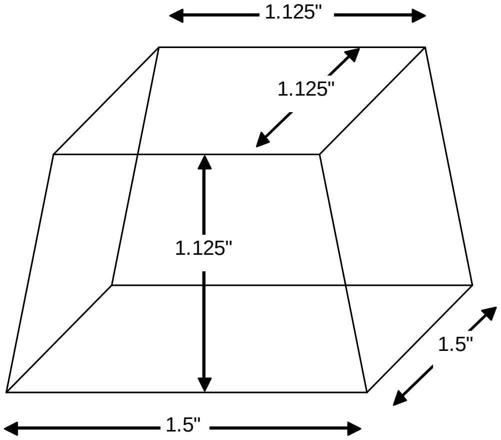
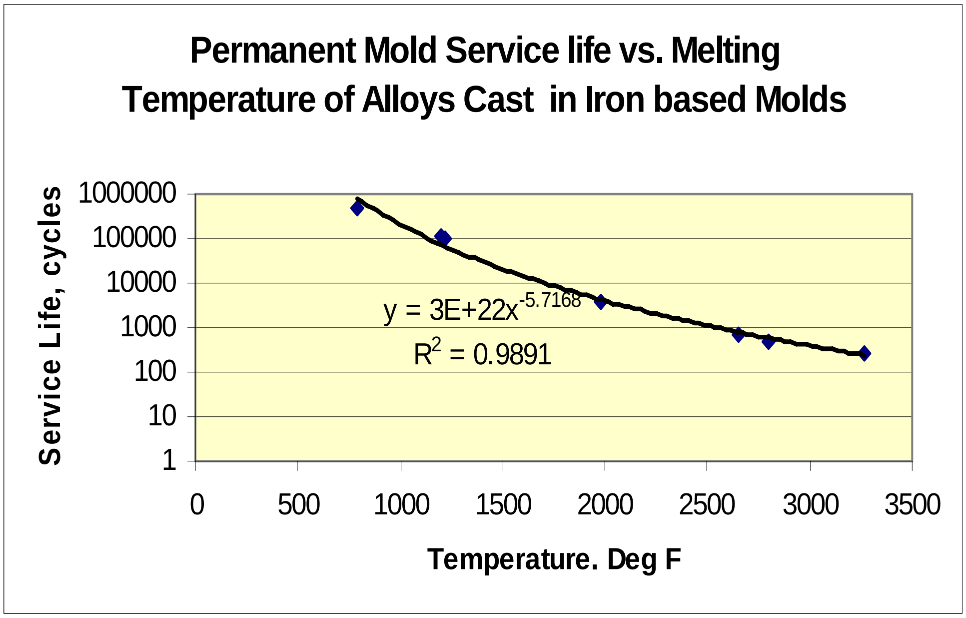


Table 1 is a tabulation of the number of casting pours/service life of an iron-based metal mold for several alloy families. Figure 3 is a plot of Table 1 that indicates that the higher the melting temperature of the alloy to be cast in a permanent mold system; the lower the service life of iron-based metal molds.

Table 1 Melting Temperature of Alloys vs Estimated Service Life (Based on Iron Metal Molds)

Alloy System	Melting Temp (ºF)	Casting Runs/Service Life
Titanium	3270	250
Iron	2802	500
Nickel	2651	700
Copper	1981	4000
Aluminum	1220	100000
Magnesium	1202	110000
Zinc	787	500000

Figure 3 Melting Temperature of Alloys vs Casting Runs/Service Life of Iron-Based Metal Mold



2.0 Process and Testing Methodology

2.1 DESCRIPTION OF PROCESS AND TESTING EQUIPMENT

A joint three-phase program between Army Research Laboratory and CERP has been initiated to develop an economically feasible permanent mold system for high-temperature casting. The plan is divided into 3 phases that will ultimately result in a small test mold being fabricated and evaluated, followed by two or three working molds being fabricated and evaluated.

This report covers the results of the Phase 1 plan, which was the manufacturing of test coupons, durability blocks that would be inserted in test molds (Phase 2). A survey of materials for use as molds was evaluated based upon the following criteria: hardness, thermal conductivity, coefficient of expansion, phase/volume change, eutectic reaction, melting point, cost of alloy, machineability, and repairability. In addition to these attributes, industry experience in high temperature permanent mold casting was incorporated into the selection criteria. The need of cooling for adequate solidification rate was determined.

The selected candidate materials were fabricated using a laser consolidated powder deposition process into durability blocks (1.5" x 1.5" at base, 1.125" height with 1.125" x 1.125" at the top, and 0.1875" radius on horizontal and vertical edges). In laser consolidated powder deposition, a high power laser is used to melt metal powder supplied to the focus of the laser beam through a deposition head. The laser beam travels through the center of the head and is focused to a small spot. Metal powders are delivered and distributed around the circumference of the head.

A variety of materials can be used such as stainless steel, Inconel, copper, aluminum, or titanium. Of particular interest are reactive materials such as titanium. Materials composition can be changed dynamically and continuously, leading to objects with properties that might be mutually exclusive using classical fabrication methods.

This technology has the ability to fabricate fully-dense metal parts with good metallurgical properties at reasonable speeds. Objects fabricated are near net shape, and have good grain structure.[1] A test mold will be designed and constructed in Phase 2 to hold four inserts for evaluation per casting run.

The Phase 1 tasks conducted by CERP were:

1. Canvass the foundry industry for information on mold materials.
2. Quantify the waste stream reduction resulting from the use of permanent molds
    a. Estimate the cost savings that can be realized as a result of waste reduction.

The Phase 1 tasks conducted by ARL were:

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[1] Anonymous. "Laser Engineered Net Shaping™." *Castle Island's Worldwide Guide to Rapid Prototyping*. 28 September 2004. http://home.att.net/~castleisland/home.htm.

1. Obtain powder for the candidate materials.
2. Fabricate durability blocks (1.5” x 1.5”at base, 1.125” height with 1.125” x 1.125” at top, and 0.1875” radius for horizontal and vertical edges).

3.0 Results

A survey of materials for use as molds was evaluated based upon the following criteria: hardness, thermal conductivity, coefficient of expansion, phase/volume change, eutectic reaction, melting point, and cost of alloy, machineability, and repairability (Table 2).

Table 2 Candidate Alloys for Durability Test

Properties relative to titanium alloys (H=higher, S=same, L=lower)

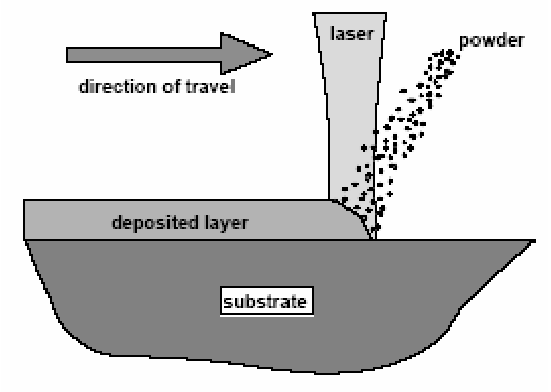
Alloy	**Conductivity**	**Hardness**	**Melt Point**	**Phase/Vol Change**	**Eutectic Reaction**	**Cost of Alloy**	**Machin-ability**	**Repairability**
Anviloy	L	H	H	None	None	H	L	L
Tantalum	L	H	H	None	None	H	L	L
TZM Moly	L	H	H	None	None	H	L	L
CuBe	H	L	L	Yes	None	S	H	S
Ampco 940	H	L	L	Yes	None	S	H	S
17-4PH	L	S	L	Yes	Some	S	H	H
H13	L	S	L	Yes	Some	S	S	S
Cast Iron	L	L	L	Yes	Some	L	H	Replace
1018	L	L	L	Yes	Some	L	H	Replace

The assessment, based on the Table 2 data and industry experience resulted in selection of refractory alloys and a baseline alloy. The selected materials are:

1. Anviloy (tungsten alloy)
2. TZM (molybdenum alloy)
3. Tantalum (pure)
4. H13 (baseline)

Except for Anviloy, which will be machined from a stock piece, the durability blocks were fabricated by means of laser consolidated powder deposition, as shown by Figure 4.

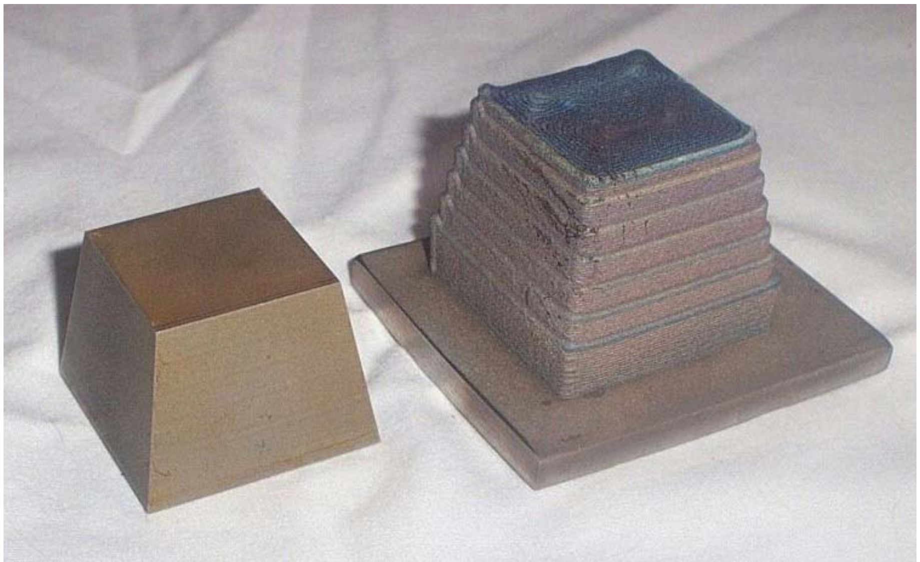
Figure 4 Intelligent Laser Process



In this method, the powdered metal is deposited, followed by laser consolidation. This process combines a 3 KW Nd: YAG laser, a Fanuc M16i Robot, and two metal powder feed systems to allow the direct metal deposition, solid free-form fabrication, and graded alloy development of metallic materials. The system was developed and is operated by Dr. James Sears at the Advanced Materials Processing Center (AMPC) of the South Dakota School of Mines and Technology and is called the Intelligent Laser Process.

Dr. Sears has fabricated durability blocks, which are shown in Figure 5. This figure shows one coupon as produced by the Intelligent Laser Process and a second coupon that has been machined to final dimensions. The deposition of Tantalum powder resulted in some over temperature warpage of the base plate and requires a slower rate of heat input. This will be accomplished with a new set of base plates. TZM powder and plates are at AMPC and will be consolidated shortly.

Figure 5 H13 Durability Blocks – Machined and Laser Consolidated



4.0 Discussion of Future Testing

4.1 NEXT PHASES OF TESTING AND ULTIMATE GOAL FOR PROCESS

Phase 2 of this project will consist of inserting durability blocks into a simple test mold and pouring cast iron into mold over multiple cycles. The Army Research Laboratory (ARL) will document the condition of each coupon prior to the initiation of metal pouring. Re-examination will be carried out after 3 months of pouring activity and any deterioration will be documented. Before and after characterizations will consist of hardness, dye penetrant inspection, and microscopic examination. Microphotographs will document visible cracking.

CERP Goals for Phase 2:

1. Identify candidate parts for the permanent mold process.
2. Design and construct a durability test mold to hold four durability blocks.
3. Pour iron into molds for evaluation of materials reaction and to establish the best material for the Phase 3 casting trials.

Phase 3: Molds for more complicated castings will be fabricated in the third phase of the plan. The molds will be created from material based upon the results learned in Phase 2. The castings and mold will be evaluated after pouring.

It is expected that this will be a demonstration phase and that the technique will be available for commercial use following this phase. Resulting castings will be evaluated for grain structure and strength. The parameters that will be investigated are die material characteristics, mold thickness, coating composition if used, and heat treatment effects.

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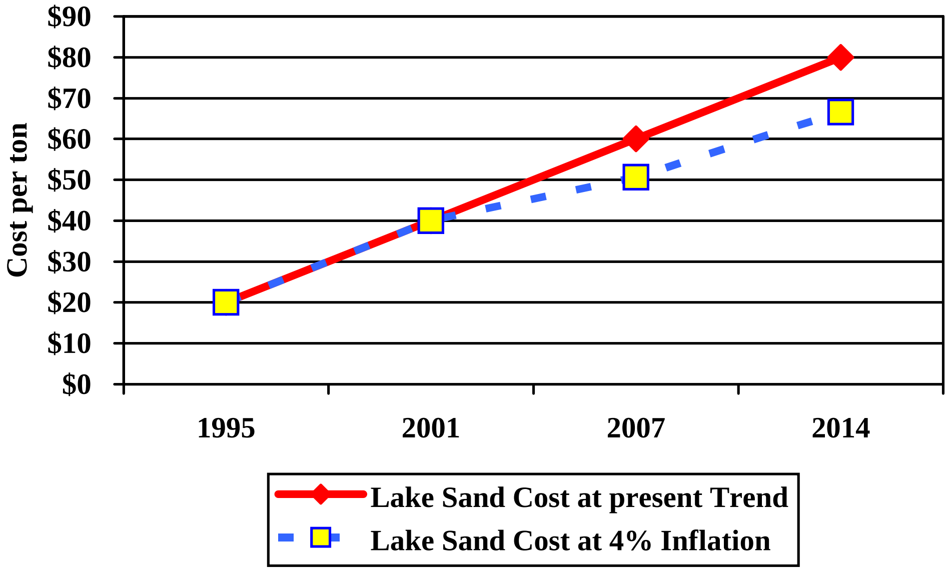
APPENDIX A COST OF SAND PURCHASE AND DISPOSAL

Foundries in Europe and Japan have been reclaiming sand because the purchase and disposal costs in those countries equal over $100 dollars per ton of sand. U.S. foundries are fortunate to be located close to high quality sand suppliers (Michigan and Illinois) and are able to purchase and dispose of sands for $35 to 40 dollars per ton.

Over the past few years sand suppliers have been forced to raise the price of Lakesand due to the mining of sand from the Great Lake sand dunes areas. This is the most popular sand used by large automotive foundries. The potential exists, that midwestern foundries may not have access to dune Lake sand in the future and may have to rely on other sources, at even higher cost.

Figure 1 reflects the historical and the projected costs (at a 4% inflation rate and a projection of the present trend) of Lake sand purchase and transportation for a typical automotive foundry.

**Figure 1: Historical and Projected Lake Sand Costs ($/ton)
Including transportation to site**



In addition to the costs of purchasing and transporting Lakesand to the site where it is used, there are additional costs for transportation and disposal of the sand after its use (i.e., waste sand) in landfills. At one large foundry this cost is $24 per ton and they own the landfill. The total cost to purchase and dispose of sand at each foundry will vary. But the minimum cost is in the range of $35 per ton of sand purchased. This cost will be used in the future cost benefit analysis completed in Phase 3 of the study which will calculate the number of sand molds eliminated by permanent molds.