**DOE/ID/12869-3
(DE94004342)**

**EXPANDABLE PATTERN CASTING RESEARCH-PHASE II
Final Report for the Period October 1, 1990–March 31, 1993**

Work Performed Under Contract No. FC07-89ID12869

**For
U.S. Department of Energy
Office of Industrial Technologies
Washington, D.C.**

**By
American Foundrymen's Society
Des Plaines, Illinois**

and

**Southern Research Institute
Birmingham, Alabama**

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Report No.: SRI-MMER-93-282-7184F

To: American Foundrymen's Society
505 State Street
Des Plaines, IL 60016-8399

Date: October 1993

CEB/njk

7184SUM.DOE

ABSTRACT

A consortium of casting producers, casting users, and foundry suppliers was formed in 1989 with financial assistance from the Department of Energy (DOE). The program objective was to develop an engineering understanding of the process and solve some of the common casting problems.

An air gauging system was developed for accurately and precisely measuring foams patterns. The exact shrinkage in foam patterns was found to be a function of the type and density of the foam used to produce patterns.

Compaction studies on laboratory scale flasks using a unidirectional vibration table showed that maximum sand densities in cavities and under overhangs are achieved with vibrational amplitudes between 0.001 and 0.004 inches. Compaction studies on a pilot line compactor table with full size steel flasks showed that sand moved most freely within a few inches of the top free surface.

The key to assuring complete mold filling while minimizing casting defects lies in removing the foam decomposition products. If the decomposition products are removed too quickly, the back pressure offered to the liquid metal is low and the metal-foam interface is no longer smooth. Metal flow will become turbulent, and the decomposition products are trapped in the casting which leads to internal defects.

The most precise iron castings were made by the EPC process in four commercial EPC foundries. These results showed that EP iron castings could be precise, but they were not necessarily precise unless attention was paid to details associated with molding and compaction.

EP cast 60-45-12 ductile iron exhibited similar yield strengths, ultimate strengths, and elastic modulus values compared to conventionally cast ductile iron cast from the same ladle.

PRECISION EXPENDABLE PATTERN CASTING TECHNOLOGY

SUMMARY OF RESULTS

The Expendable Pattern Casting (EPC) Process is a developing foundry technology that allows designers the opportunity to consolidate parts, reduce machining, and minimize assembly operations. The process also allows foundries to significantly reduce solid wastes and environmental emissions.

The EPC process has been successfully used for about ten years to produce aluminum castings for automotive and marine engines. There have been some remarkable successes with the EPC process and a few significant failures. The Saturn Corporation is producing aluminum heads and blocks, ductile iron crankshafts, and other parts with the EPC process. This process can produce dimensionally accurate and precise castings, but it can also, without proper control and attention to process detail, produce warped, distorted, and defective castings.

A consortium of casting producers, casting users, and foundry suppliers was formed in 1989 with financial assistance from the Department of Energy (DOE). The program objective was to develop an engineering understanding of the process and solve some of the common casting problems.

The most significant results of the project are outlined as follows:

Gauging System and Foam Stabilization

1. An air gauge system was developed for accurately and precisely measuring foam patterns. The air gauge was used to measure the shrinkage characteristics of test patterns, commercial patterns, and castings made from these patterns. The air gauge applied low loads to foams to minimize deflection or distortion during the measuring process. The system precision was approximately 0.0005 in.
2. The exact shrinkage in foam patterns was found to be a function of the type and density of the foam used to produce patterns.

Pattern Blowing and Stabilization

3. Good surface bead fusion on foam patterns was found to be important. Deep triple points between beads resulted in coating penetration which led to internal gas generation and lower casting fatigue properties.
4. Foam patterns expanded for a period after being blown in, stabilized for a few hours, and then began to shrink. Castings could be poured during the initial stable period if foundries could control the molding process.

5. Beads preaged for periods of greater than 8 hours did not expand as much upon removal from the tool as batches aged for shorter periods of time. However, after about a week, all parts produced from a particular bead stock had approximately the same dimensions irrespective of bead preaging time.
6. Patterns continued to shrink even after 10 weeks aging time. The rate of shrinkage was low, but measurable. Complete dimensional stabilization did not occur in the commonly used four week stabilization period.

Sand Fill and Compaction

7. Sand deposition by pluviation through screens of various sizes and from various drop heights showed that maximum sand density can be achieved by free fall through a 10 mesh screen using drop heights of up to 34 inches. However, pluviated sand did not fill pattern cavities or flow under overhangs.
8. Compaction studies on laboratory scale flasks using a unidirectional vibration table showed that maximum sand densities in cavities and under overhangs were achieved with vibrational amplitudes between 0.001 and 0.004 inches. Pluviation had little effect on sand densification when vibration was used to move sand into pattern cavities.
9. Compaction studies on a pilot line compactor table with full size steel flasks showed that sand moved most freely within a few inches of the top free surface. Additional energy was required to unlock densified sand beneath the free surface to fill cavities.
10. Bulk sand flowed from the top toward the bottom of a flask unless the sand was progressively densified during fill and compaction. Bulk sand movement was found to be the source of pattern deformation.
11. Pattern cavity fill rates were proportional to flask acceleration, but pattern position and orientation in the flask had a significant effect. Flask maps can be developed to determine areas of high and low sand activity in flasks.
12. Cavities filled more quickly with 2 inches of sand burden as compared to 6 inches. Tailoring the fill and compaction cycle to the position of pattern cavities was important in optimizing compaction.
13. Flask vibration was disturbed by the action of sand inside flasks even when flasks were clamped to the table. Studies on both bench scale and commercial flasks showed that the sand impacts flask walls and interferes with the input excitation. The sand was also found to act somewhat independently of the flask.

14. Bulk sand flow usually occurs upwards along the flask centerline and downward at the flask walls. This motion was found in both vertical and horizontal compactors and had previously been attributed to an "oil can" effect where the bottom of flask acted as a diaphragm pump. However, the real reason for sand flow up the centerline was found to be the impacting of compression waves at the flask centerline.
15. Consistent flask deformations were observed in bench scale flasks, pilot line flasks, and the industrial flasks when the input accelerations were either impact events or sine waves. Flask sidewalls 90° apart always acted as diaphragms 180° out of phase.
16. Once densification is complete and sand grains locked up, extra energy is required to cause sand movement to fill internal pattern cavities.

Gating, Coating, and Pouring

17. Care must be taken in designing gating systems to minimize the occurrence of liquid metal streams meeting within the casting cavity. Some pattern residue is carried on the leading edge of flowing metal streams. When two streams meet, residue is often trapped at or near the line of contact.
18. The key to assuring complete mold filling while minimizing casting defects lies in removing the foam decomposition products. If the decomposition products are removed too quickly, the back pressure offered to the liquid metal is low; the metal-foam interface is no longer smooth; metal flow becomes turbulent; and the decomposition products are trapped in the casting.
19. While the characteristics of the foam help determine the volume and nature of the decomposition products that must be removed, the properties of the refractory coating are crucial for determining the rate at which the products can be transferred from the casting cavity. The liquid polymer must wet and wick into the coating, while air and gaseous decomposition products must diffuse through the coating to escape the metal front. These factors depend to a great extent on the permeability of the coating.
20. The rate of coating infiltration by pattern pyrolysis products depended on the coating temperature and the type of coating. The depth to which the polystyrene infiltrated the coating increased with the square root of time. The rate increased with increasing temperature and with increasing coating permeability.

Casting Precision and Accuracy

21. The most precise (repeatable) aluminum castings were made by the EP process using 1.6 pounds per cubic foot (pcf) expanded polystyrene (EPS) foam. This was followed by commercial aluminum castings made in no-bake and green sand molds.

22. Slightly better casting accuracy (conformance to expected casting dimensions) was obtained with sand cast aluminum compared to EP cast aluminum because localized variations in foam contraction (which a priori were not anticipated) caused variations in the pattern dimensions. The variation in accuracy was corrected with minor adjustments to the tool dimensions.
23. The most precise iron castings were made by the EPC process in four commercial EPC foundries. These results showed that EP iron castings were not necessarily precise unless attention was paid to details associated with molding and compaction.
24. When special attention was paid to the compaction process to minimize pattern distortion, the accuracy and precision of EP castings was as good as obtained in the best no-bake molds.

EP Casting Properties

25. EP cast 60-45-12 ductile iron exhibited similar yield strengths, ultimate strengths, and elastic modulus values compared to conventionally cast ductile iron cast from the same ladle.
26. Fully machined fatigue specimens exhibited the best fatigue life.
27. As-cast surfaces (EPC and sand) reduced fatigue strength (B50 stress amplitude) by 30-40% compared to machined specimens.
28. Fatigue failures on as-cast EPC fatigue specimens began at bead triple points where coating penetrated in between the beads to produce a pit on the cast surface. Smoother patterns were required to improve the fatigue properties of as-cast parts.

Additional details of the program in the context of the EPC process are given in subsequent sections of this report.

ACKNOWLEDGEMENTS

We wish to express grateful acknowledgement and deep appreciation to the many companies and individuals who participated in the project by providing advice, descriptions of particular difficulties, defects, and guidance regarding the most fruitful areas for investigation.

A special word of thanks goes to Mr. George Vingas and Mr. Dan Twarog for guidance and insight throughout the project. Mr. Raymond Monroe, currently the Executive Vice President of the Steel Founders' Society, also provided significant assistance.

We also wish to express our appreciation to the Department of Energy for technical assistance and partial funding of the project. Special thanks go to Dr. Gobind Jagtiani, Mr. Bob Trimberger, Dr. Manohar Sohal, and Mr. Jay Anderson. Matching funds were provided under contract DE-FC07-89ID12869 with Amendments.

Our hope is that the information contained in this report will be of assistance to companies throughout the United States in advancing the science of EP casting.

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1. EPC PROCESS OVERVIEW

The most popular current use of the EPC process places expanded foam patterns in compacted unbonded sand. Patterns are coated with refractory, placed in a flask, backed up with compacted unbonded sand, and liquid metal poured onto the pattern to replace the foam. A pattern refers to an expendable foam that is replaced by molten metal during pouring.

The EPC process uses expanded polystyrene (EPS), expanded polymethyl methacrylate (EPMMA), blended EPS and EPMMA, and copolymers of EPS and EPMMA to form patterns that are consumed with each casting poured.

1.1 The EPC Process Sequence

The steps involved in the EPC process are outlined in Table 1. The first step in the process is to design the part. After the part is selected and designed, it is necessary to design tooling to make the sections of foam required for the pattern. Tool design for foam production is important because it fixes the initial foam dimensions and influences foam pattern quality, surface and internal bead fusion characteristics, and production cycle time.

Complex casting designs may require that several foam sections be made separately and glued together to form the pattern. Each foam section requires a tool for production. A second tool or fixture may be required to maintain alignment during gluing operations.

The production of molded foam sections is a two-phase process. The foam most commonly used at the present time is polystyrene containing about 5-8% pentane and PMMA with hydrocarbon expanding agents. The first phase is to expand the as-received polymer beads to the desired use density. Aluminum casting producers commonly prefer an EPS density of 1.4-1.6 pcf (22.4-25.6 g/L), and iron casting producers prefer a density of 1.0-1.3 pcf (20.8 g/L). Most PMMA is expanded to a density of about 1.5-1.8 pcf (24-29 g/L).

Bead expansion is accomplished by rapid steam heating, and the resulting beads must be stabilized before use. The initial bead expansion step is called preexpansion, and the resulting product is called prepuffed or preexpanded beads. After stabilization, the beads are ready for use.

Many quality problems begin at the foam making part of the process. The beads must be properly expanded, stabilized, and blown into the tool block. The tool venting must be adequate to allow the air in the tool cavity to escape. Fill guns must also be properly placed and regulated to achieve filling of the cavity.

In phase two the tool cavity is filled with beads and the steam cycle is begun. Steam is passed from one side of the tool to the opposite side through vents, and then the steam blowing direction is reversed. The steam causes the beads to soften, expand to fill the interparticle voids, and bond together. After fusion, steam is simultaneously blown from both sides of the tool and

TABLE 1. STEPS IN THE EPC PROCESS

- I. PART DESIGN
- II. DIE DESIGN AND PRODUCTION
- III. PREPARE FOAM SECTIONS
 - A. PRE-EXPANDED BEADS
 - B. MOLD BEADS
- IV. ASSEMBLE SECTIONS/CLUSTER
- V. COAT CLUSTERS
- VI. FILL AND COMPACT SAND
- VII. POUR
- VIII. SHAKEOUT AND FINISH THE CASTINGS

the pressure raised. This causes the tool surface temperature to rise, the pentane to further expand the beads, and the bead surfaces to fuse. This process step is referred to as the autoclave step. Care must be taken during autoclaving to prevent overheating that can cause surface bead collapse.

After steaming, the foam pattern must be cooled. This can be achieved with water sprays on the back of the tool or by the application of a vacuum. The tool is then opened, the pulls extracted, and the foam ejected. The foam is still warm and soft, so care must be taken during ejection and storage to minimize distortion.

After the initial foam shrinkage caused by tool cooling, the foam pattern expands for a short time as air diffuses into the beads, and then shrinks again as pentane and water vapor diffuse out. Most of the shrinkage occurs within 30 days and amounts to about 0.8% linear contraction in EPS patterns and 0.25% in EPMMA. Control of the shrinkage is necessary to achieve dimensional consistency and gain the full benefit of the process.

The foam sections are ready for assembly after dimensional stabilization. Assembly requires the same precision needed in the cast part. Sections are typically glued together on automatic machines using a hot melt glue. The glue joint must be sufficiently strong to hold the part together, be fast setting to maximize the production rate, seal joints against penetration of the ceramic coating, and have minimal mass to minimize contributions to casting defects.

The coating is usually a slurry of refractory in a water carrier and is applied to the foam cluster by dipping, spraying, or pouring over the pattern. After the coating has been applied, it must be completely dried. Careful control over this process is necessary to obtain a uniform coating layer on each cluster because coating thickness affects coating permeability for both gases and liquids and hence final casting quality.

It is possible for coatings to dry in a low humidity room, but the most common drying method consists of passing the coated foam through a circulating air oven. The cluster normally takes from 2 to 10 hours to dry at 100-140°F (40-50°C). A useful coating control method is to determine the wet and dry coating weight on the cluster.

The dried coated cluster is ready to be placed in a flask and backed up with sand. Cluster placement, filling the flask with sand, and sand compaction must be accomplished so that the sand fills all internal cavities and packs tightly around the cluster to provide support. The sand filling and compaction cycle for each cluster design is important. The sand may be rained from above through a screen or supplied through tubes placed around the cluster. The rate of filling and the distribution of sand in the flask can have a significant effect on pattern deformation.

Compaction is usually achieved using a vibrating table. The flask may be placed on locator pads on the table or clamped to the table. There is considerable controversy about the utility of vibrating flasks in a clamped or unclamped condition. Some investigators have concluded that rigidly clamped

flasks produce a more repeatable compaction cycle, but it has not been conclusively shown that clamped flasks produce better molds than well-controlled, vertically vibrated, unclamped flasks. Compaction is usually done during filling to help sand flow into internal pattern cavities.

After a cluster is backed up with sand, the mold is ready to be poured. Pouring consistency is more critical with the EPC process than in conventional foundry practices, and automatic pouring ladles are commonly employed to minimize pour-to-pour variations. If pouring is interrupted, the sand may collapse into the casting cavity. The pouring rate must be as rapid as possible to avoid mold collapse but sufficiently slow to allow the foam pyrolysis products to escape. The gating system, coating properties, sand properties, and pouring operation must operate as a system to allow both liquid and gaseous pyrolysis products to escape from the cavity.

After pouring, the casting cluster is allowed to solidify and cool in the flask prior to being shaken out. Shakeout of EP castings is relatively simple. Shakeout is usually a matter of dumping the flask and lifting the castings out of the loose sand. Once the sand has cooled, it can be reused again with little or no additional preparation. Cleaning is typically easier and requires fewer operations since there are no fins or parting lines to grind and blend into the casting contour. The loose sand in the internal cavities is more easily removed than the lumps of bonded sand that remain in cores made with chemical binders.

2. PATTERN MAKING AND STABILIZATION

2.1 Foam Preexpansion

The production of foam patterns is a two step process. The first step involves preexpansion of beads to make foam spheres of the desired bulk density. The second step involves molding and fusing the beads into the desired pattern shape. During molding, the beads are expanded with steam to fill the interparticle void space and fuse the bead surfaces together.

Preexpansion is a critical operation that establishes the bulk density and the moldability of the foam. During expansion, beads are heated to cause the bead honeycomb structure to soften and the blowing agent to expand inside the soft shell. Careful control of bead heating and cooling is necessary to achieve the correct bead density.

Control of the pentane content is necessary for proper preexpansion, molding, and aging. The raw bead is commonly supplied containing about 5-8% pentane, and lower density foams require higher pentane concentrations. Approximately 1-2% of the pentane is lost during preexpansion. Molding causes an additional loss of pentane, and molded sections usually contain about 1.5% pentane. The pentane content typically falls to 0.5% after 30 days of storage. The loss of pentane is one of the factors in pattern shrinkage after molding.

When polystyrene is heated with steam, the pentane is gasified at about 175°F (80°C) and the boiling pentane causes bead expansion. The beads are normally expanded from 20 to 50 times their original volume to achieve densities of 1.2-1.7 pcf (19-27 g/L).

Beads cannot be molded immediately after preexpansion. Bead cooling, as they are removed from the expansion chamber, causes condensation of the pentane which results in a negative internal pressure. Some stabilization time is needed to allow air to infiltrate the bead structure and equilibrate the internal pressure with the external atmospheric pressure.

If the time after preexpansion and before molding is too short, beads may not expand during molding and may cause poor surface finish on the resulting foam. If the stabilization time is too long, however, excessive blowing agent may escape, and the beads will not expand properly when blown and steamed. To prevent excessive loss of blowing agent, the beads should be used within 12 hours after preexpansion. Beads over 24 hours old are seldom used in the production of quality patterns. A conditioning or stabilization period of typically 2 hours produces the best results.

Bead aging or conditioning is normally done in silos that hold one to five cubic meters of preexpanded beads. The silos are usually mesh bags supported on wooden or metal frames. The use of grounded metal frames reduces the static charges that can ignite escaping pentane.

2.2 Molding

After preexpansion, the beads are injected into a metal tool and heated to form the desired foam shape. The production of the pattern fixes the dimensions, surface finish, and shape that can be achieved in the metal casting. The appearance of well-formed and fused pattern surfaces are illustrated in Figures 1 and 2. The beads are in close contact to minimize mold wash penetration into the surface. Figure 1 (A) and (B) illustrate well-fused surfaces under a scanning microscope at magnifications of 10X and 20X, respectively. Figure 2 (A) and (B) illustrate the contact between the beads as viewed under an optical microscope. Figure 2 (B) illustrates especially uniform bead contact.

Filling the tool with beads is a critical step in the molding operation. Lack of fill results in incomplete foam sections or sections with low bead densities. Examples of incomplete fill are illustrated in Figure 3 (A) and (B). Incomplete fill is caused by an inadequate quantity of beads being blown into the tool.

The steam cycle can begin as soon as the tool cavity is filled with beads. Steam is blown from one side of the tool cavity to the other, and then the flow direction is reversed. The flow of steam through the tool cavity causes bead expansion to fill the space between the beads. Steam flow occurs through vents, around the tips of fill guns, and sometimes between slightly open tool faces. The steam heats the foam to the center causing the beads to soften, expand, and fuse together. Generally an inadequate fusion cycle results in a beady surface and inadequate foam strength.

After fusion, steam is applied to both sides of the tool during the "autoclave" portion of the cycle. The steam causes heating of the tool surface which in turn causes the beads on the surface to fuse and glaze to develop a smooth foam surface. The tool normally reaches a final temperature of 230-250°F (110-120°C) at the end of the autoclave step.

Poor fusion results in a rough, beady surface and poorly bonded internal beads. Figure 4 illustrates a poorly fused bead surface.

Incomplete bead fill or poor surface fusion usually results in subsequent coating penetration between the beads, as illustrated in Figure 5. A coating was applied to a beady foam surface, dried, and the foam removed with heat. The photograph illustrates the infiltrated coating at bead triple points. These peaks erode during pouring to produce debris and gas porosity in castings. The appearance of a coating applied to a properly fused foam surface is illustrated in Figure 6.

Several processing factors can cause poor bead fusion including an inadequate steam supply, a short steaming cycle, a cold tool, improper tool venting, and an inadequate volume of steam. Basically, poor fusion is a result of inadequate heating of the beads after injection into the tool. The lack of heat causes underexpansion of the beads and incomplete fillout of the surface of the part. If a foam section is broken after an inadequate fusion cycle, the beads in the center may not be fused together. This is referred to as underfusion.

(A)

(B)

615-470

Figure 1. Acceptable EPS Foam Surfaces, (A) 10x, (B) 20x

(A)

(B)

615-407

Figure 2. Optical Micrographs of (A) Marginally Fused and (B) Well Fused EPS Surfaces, (25x).

(A)

615-477

(B)

Figure 3. Incomplete Tool Fill.

(A)

(B)

615-478

Figure 4. Poorly Fused EPS Bead Surfaces due to incomplete fill, 10x.
Note Gaps Between Beads and Limited Bead Contact.

(A)

(B)

616-202a

Figure 5. Coating Penetration Between Poorly Fused Surface Beads.
(A) 10X (B) 50X

(A)

(B)

616-202b

Figure 6. Appearance of Coating Applied to a Properly Fused Foam Surface.
(A) 10X (B) 50X

It is necessary to cool the molded part to a point where the internal pressure in the beads is low enough that the part can be ejected without further expansion outside the tool. Thin molded parts cool quickly because of the high surface area to volume ratio. Thicker parts require longer cooling cycles in the tool if subsequent expansion is to be minimized.

The foam must be cool and stable in order to be successfully ejected from the molding machine. The use of vacuum for cooling, however, makes the cooling cycle longer than required by water flooding. Inadequate cooling results in uncontrolled dimensional variations and a rough surface on the foam section and is called postexpansion.

After cooling, the foam is ready to be ejected from the tool. Cooling the foam produces condensation of some moisture and pentane within the cells. This causes the foam to shrink away from the tool and aids ejection. The section may be forced against one side of the tool during opening by using air pressure on the opposite side of the tool.

2.3 Pattern Materials

Expanded polystyrene (EPS) is the dominant polymer used to make foam patterns. The major problems associated with EPS are carbon soot defects in iron castings, and laps in aluminum castings. The limitations imposed by the pyrolysis of polystyrene has led to studies of alternate polymers for pattern production including expanded polymethyl methacrylate (EPMMA), expanded polyethylene (EPE), and expanded polyalkylene carbonate (EPAC). Urethane foams have been used to a limited extent in EPC casting, but polymethyl methacrylate (PMMA) is the most widely used alternate to polystyrene at the present time.

A significant advantage of EPMMA in iron casting production is the reduced incidence of carbon related defects. Ductile and gray iron castings with low surface area to volume ratios and castings with wall thicknesses of more than 50 mm have been poured from EPMMA patterns without carbon related defects. PMMA has a longer shelf life in both the unexpanded resin and expanded bead foams.

The use of EPMMA requires some adjustments in the pouring operation. The formation of carbon is minimized because pyrolysis produces primarily gaseous products. The higher rate of gas production, however, requires more permeable coatings to allow gas removal. Metal spitback during pouring onto EPMMA patterns is common. This can be minimized by using higher permeability coatings, deep sprues, bottom gating, and a vacuum on the flask during pouring. Mixtures of EPMMA and EPS have been used with some success.

2.4 Dimensional Stabilization

In high production systems where foams are made locally, foam sections may be used after a short stabilizing period. Alternatively, foam sections may be aged for 15-30 days before use in lower production rate systems. Reproducible foam dimensions are the result of reproducible foam production and use conditions.

Both EPMMA and EPS contain about 8% water after the steaming operation is complete. EPMMA stabilizes with a negative dimensional change of about

0.25% after 24 hours, whereas EPS continues to change slowly in dimensions for about 30 days. The shrink rule applied to EPMMA is about 0.2% to 0.3%, and the shrink rule recommended for EPS is approximately 0.6% to 1.0%. There is very little blowing agent loss after EPMMA patterns are blown because of the relative impermeability of the cell wall.

Two patterns were chosen for dimensional stability studies in the current program. The webbed test cube pattern, schematically illustrated in Figure 7, was chosen to determine the effect of EPC process variations on casting quality.

A cone pattern illustrated in Figure 8 was selected to evaluate dimensional precision when comparing the EPC process to conventional sand casting processes. A schematic of the sand casting pattern is illustrated in Figure 9. The only difference between the EPC pattern and the molded sand pattern are the four cast-in holes on the flange, and the center hole on the top of the EPC cone.

A coordinate measuring machine (CMM) was set up in the foam production facility, and approximately 6% of the foams produced were dimensionally analyzed and the dimensional changes tracked during stabilization. The CMM apparatus is illustrated in Figure 10.

2.4.1 CMM Dimensional Analysis Procedure. The CMM turntable had a steel center shaft on the axis of rotation that served as a reference and locator for all measurements. The shaft had interchangeable mandrels to accommodate various parts to be measured. The CMM used a differential pressure sensor to locate the surface of the foam pattern or casting. After calibration, the pattern or casting was located on the tapered mandrel on the rotating table. The mandrel was tapered to match the taper of the interior surface of the test cone, and the mandrel fixed the z axis centerline of the part being measured. The cones were oriented with the starter dimples at the 12 and 3 o'clock positions on the mandrel. The micro-processor-controlled sensor measured the radial surface position of each pattern or casting location corresponding to 0, 90, 180, and 270° around the casting periphery. The measured dimensions were stored on magnetic media for analysis. The EPC patterns were measured as a function of time after production, and again immediately before shipment to the foundry. The resulting castings were measured to determine the dimensional variations in the castings produced.

Sample data illustrating measurement precision are presented in Table 2. These measurements were made on a well-stabilized two year old cube. The cube was removed from the machine between each measurement to obtain data on total system precision. The standard deviation in measurements on each face of the cube was approximately 0.0014 inches and the coefficient of variation was about 0.048%. The high precision was a result of the system accuracy and the low load applied to foams when measurements were made.

Dimensional change data on 17 EPS cubes made with a density of 1.3 pcf is illustrated in Figure 11. The cubes were initially approximately 0.8% under the room temperature tool dimension and gradually expanded until they were approximately 0.4-0.5% undersized. They then began contracting again and after 10,000 minutes (1 week), the cubes were approximately 0.70% under the

BP RINT A

Figure 7. Webbed Test Cube Pattern.

cone5

Figure 8. EPC Test Pattern for Dimensional Analysis

cone6

Figure 9. Sand Casting Test Pattern for Dimensional Analysis.

615-497b

Figure 10. Microprocessor Controlled Portable Coordinated Measuring Machine.

Table 2.
CMM Precision Data on Stabilized EPS Webbed Cube

Reading Number	Dimensions from Center Line (Inches)				Time
	0°	90°	180°	270°	
1	3.030	3.037	3.054	3.035	13:33:47
2	3.030	3.037	3.056	3.037	13:41:49
3	3.034	3.039	3.053	3.035	13:48:58
4	3.030	3.037	3.053	3.035	13:55:32
5	3.030	3.036	3.054	3.035	14:02:13
6	3.033	3.039	3.053	3.034	14:08:42
7	3.030	3.035	3.052	3.034	14:15:27
8	3.030	3.037	3.052	3.032	14:22:11
9	3.033	3.036	3.051	3.035	14:29:19
<hr/>					
$\bar{x}$ (in)	3.0314	3.0370	3.0531	3.0347	
σ (in)	0.0017	0.0013	0.0014	0.0013	
CV (%)	0.056	0.043	0.047	0.044	

where $\bar{x}$ - Average,
 σ - Sample standard deviation,
 CV (%) - Percent coefficient of variation.

Figure 11. Percent Dimensional Changes from Cold Die Block Dimensions in 17 EPS Test Cubes Molded to a Density of 1.3 pcf.

615-498-R3

tool dimension. After 140,000 minutes (14 weeks), the cubes were about 1% under the tool centerline to face dimension. This is slightly higher shrinkage than reported in the literature.

Similar data on 16 EPS cubes molded to a density of 1.6 pcf are shown in Figure 12. These cubes were initially undersized by approximately 0.55% and gradually expanded over about 1,000 minutes to approximately 0.2% below the tool dimension. At this point the cubes began shrinking again and, after 10,000 minutes (1 week), they were approximately 0.60% under the tool size. After 14 weeks the foams were approximately 1.05% undersized.

It was observed that the EPS foams were dimensionally stable from about 100 to 2000 minutes after production. This suggests the possibility of coating the foams with a stiff ceramic coating during this time interval to "freeze" dimensions and perhaps permit pouring castings without waiting the normal four week pattern stabilization time.

Dimensional change data on EPMMA at a density of 1.5 pcf is illustrated in Figure 13. The EPMMA foams were approximately 1.5% undersize immediately after removal from the tool and gradually expanded over 10,000 minutes until they were under the tool size by approximately 0.8%. While there is some scatter in the data, the EPMMA foam stayed reasonably stable over the period of 1000 to 140,000 minutes.

2.4.2 Foam Cone Pattern Stabilization. Four foam cone dimensions, illustrated in Figure 14, were selected for tracking the dimensional changes occurring during aging. The "A", "B", and "C" dimensions represent cone diameter measurements at progressively greater distances from the fill gun. The "H" dimension is the height of the cone from the bottom of the flange.

Average dimensional changes in 1.3 pcf EPS are illustrated in Figures 15 through 17 for the "A", "B", and "C" dimensions, respectively. The "A" dimension was initially about 0.5% larger than the tool dimension and shrunk with time to about 0.1% over the tool dimension after five weeks (50,000 minutes) as illustrated in Figure 15. The "B" dimension, as illustrated in Figure 16, was similar to the "A" dimensional changes, stabilizing at about 0% shrinkage after five weeks.

"C" dimensional changes for 1.3 pcf EPS are illustrated in Figure 17. The "C" dimension was initially about 0.75% under the tool dimension, expanded slightly between 100 minutes and 1,000 minutes after removal from the tool, and then began to shrink. After about 5 weeks, the "C" dimension was approximately 1.00% under the tool dimension. Similar results were obtained with 1.6 pcf EPS.

Dimension "A", which was closest to the fill guns, was actually larger after removal from the tool than the tool dimension itself. This was probably because beads were compacted more tightly in this location and immediately expanded after part removal from the tool.

The mean and standard deviation in pattern dimensions in each group of foams after aging about five weeks is presented in Table 3. The coefficient of variation in each measurement was below about 0.3% or 0.003 in/in in all

Figure 12. Percent Dimensional Changes from Cold Die Block Dimensions in 16 EPS Test Cubes Molded to a Density of 1.6 pcf.

615-500-R3

Figure 13. Percent Dimensional Changes from Cold Die Block Dimensions in 16 EPMA Test Cubes Molded to a Density of 1.5 pcf.

615-707

Figure 14. Dimensional Measurements Made to Track Foam Changes.

Figure 15. Average "A" Dimensional Changes in 12 1.3 pcf EPS Cone Test Patterns.

615-708-CR1

Figure 16. Average "B" Dimensional Changes in 12 1.3 pcf EPS Cone Test Patterns.

615-711-R1

Figure 17. Average "C" Dimensional Changes with Time in 12 1.3 pcf EPS Cone Test Patterns.

TABLE 3.

Mean And Standard Deviation In Foam Cone Dimensions
After Aging Approximately 58,000 Minutes (5.8 Weeks)

		"A"	"B"	"C"
1.3 pcf EPS	X	0.884	1.763	3.564
	S	0.002	0.003	0.003
	N	12	12	12
	CV%	0.260	0.142	0.081
1.6 pcf EPS	X	0.884	1.763	3.565
	S	0.003	0.003	0.004
	N	13	13	13
	CV%	0.305	0.193	0.101
1.5 pcf EPMMA	X	0.884	1.767	3.573
	S	0.005	0.005	0.004
	N	12	12	12
	CV%	0.600	0.289	0.123

where X - Average
S - Sample standard deviation
N - Number of observations
CV% - Percent coefficient of variation

615-719.TAB2

cases except for the "A" dimension on EPMMA foams. This value was about 0.60% or 0.006 in/in.

2.4.3 Application of Air Gauging to Commercial Patterns. Prior to the development of the air gauging system, it was difficult to make systematic bead or foam process variations and track part dimensions with time. Freshly blown foams are soft and easily deformed by the stylus on coordinate measuring machines. Furthermore, coordinate measuring machines are relatively slow and require substantial amounts of time to make several measurements on a particular foam.

However, air gaging systems apply small forces and with multiple sensors many readings can be made in short periods of time. An air gauging system developed by Matrix Technologies (Muncie, Indiana) was used to measure foam changes on a section of a commercial engine block pattern. The system had six sensors mounted on each of two gauging fixtures. A set of dimensional measurements could be made on a pattern in about 15 seconds.

Experiments were conducted to define the effects of bead type and processing on part dimensions and foam shrinkage after blowing. The material examined was commercial EPS beads at a density of 1.6 pounds per cubic foot (pcf).

The part produced was a three cylinder lower block section illustrated in Figure 18. The "A" and "B" dimensions were the distances between bore radii along the centerline of the block. The "C" dimension was the distance from the end bore radius to the end of the block. The "W1" and "W2" dimensions were block section widths at two different positions, and the "L" dimension was the overall block length.

The bead stock was preexpanded using steam. After ejection of the beads from the pre-expander, they were screened, blown into a bag and transferred from the bag into cardboard containers for aging. Twenty parts were blown from each batch of beads after prepuff aging times of approximately 2, 4, 8, 12, 24 and 48 hours.

The various groups of foam patterns were labeled according to the type of bead, bead processing prior to blowing, and prepuff age at the time of blowing. The series "A" beads were preexpanded from stock containing 6% pentane and aged at 75°F for two hours prior to blowing. Batch A-02 refers to series A beads that were aged approximately two hours prior to blowing. Batch A-12 refers to the same bead stock aged 12 hours prior to blowing.

As each part was blown, a unique label was applied indicating the foam batch number, the individual part number in the batch, and the time the part was blown. Dimensional changes of parts were measured and reported as a function of lapsed time after blowing.

2.4.3.1 Dimensional Measurements. The air gauging system incorporated primary and secondary air chambers and two orifices (first and second) to make dimensional measurements. The primary pressure chamber was located before the first orifice. This chamber pressure stayed relatively constant (± 0.05 psi) during operation. The secondary pressure chamber was created by the gas

Figure 18. Schematic of Lower Block Section Foam with Dimensions.

volume in the air line between the first and second orifice. The secondary chamber pressure varied according to the amount of air leaving the second orifice.

The first orifice was the smaller of the two orifices in the system. Both orifices consisted of square edged (critical flow) orifice plates that maintained a constant gas velocity.

When the gap between the second orifice and a part was zero, the flow of air was shut off, and the pressure in the secondary chamber was equal to the pressure in the primary chamber. The ratio of the primary pressure to the secondary pressure was then 1/1 or 1. When the gap was opened, air flow began and the pressure in the secondary chamber dropped. This produced a pressure ratio greater than 1.

The system was calibrated by measuring pressure ratios as a function of gap opening. A computer was used to curve fit the data with up to a 10th order least squares polynomial. The calibration curve was then divided into 2,500 segments, and a look-up data table was prepared to relate the gap opening to the measured pressure ratio. The "look-up" table allowed quick determinations of the gap opening from the pressure ratio.

After calibration, the measurement process was as follows: a part was placed near a sensor with a gap between the part and the sensor in the range of 0 to 0.070 in. The circuit board in the manifold received pressure signals from the primary chamber (which was shared by all channels) and six pressure transducers connected to secondary chambers (which provided six channels of simultaneous data). The circuit board converted the pressure transducer output to digital signals and sent this information to the computer. The computer calculated each pressure ratio (primary chamber/secondary chamber) and determined the gap between the part and the orifice from the look up table.

Two opposing sensors were placed a known distance apart to measure part thickness or length. When a pattern was placed between the sensors, two gaps were measured. The formula (Part thickness = X-A-B) applies where X is the total distance between the two sensors, A is the first sensor gap and B is the second sensor gap. X is measured during setup usually with a coordinate measuring machine. If the part moves toward the first sensor, that gap becomes smaller but the second gap becomes larger by the same amount. This allows differential measurements to be made using two transducers independent of the position of the pattern between the two transducers.

2.4.3.2 Gauge Repeatability and Reproducibility (R & R). The gauge repeatability and reproducibility was determined by taking ten foams from batch A-02 and measuring each foam five times using two different machine operators. The standard deviation in both the "A" and "B" dimensions was 0.0005 inches. The standard deviation in the "L" and "W1" dimensions was 0.0006 inches. The standard deviation in the "W2" dimension was 0.0002, and the standard deviation in the "C" dimension was 0.0003 inches. The average standard deviation in the measured dimensions of parts was approximately 0.0005 in.

2.3.3.3 Shrinkage and Expansion Calculations. Foam dimensional changes were calculated from room temperature tool dimensions obtained by removing the tool from the foam blowing machine and making measurements on a coordinate measuring machine. There was some uncertainty in the exact tool dimensions because of the difficulty of placing the slides into exactly the same position used when the tool was mounted and parts were being blown.

The "true" foam expansion or contraction was calculated using the logarithm of the foam dimension divided by the tool dimension, as shown in Equation 1.

$$\epsilon' = \ln (L/L_o) \quad (\text{Eq. 1})$$

The following manipulations show the relationship between true shrinkage and engineering shrinkage:

$$\epsilon = \exp (\epsilon') - 1 \quad (\text{Eq. 2})$$

The deformations given throughout this report are "true" shrinkage. These values can be converted to engineering shrinkage by exponentiating the reported value and subtracting 1.0 from the result, as shown by Eq. 2.

2.4.3.4 Variance in Dimensional Measurements and True Shrinkage. Six batches of data on foam groups A-02, A-04, A-08, A-12, A-24, and A-48 were analyzed in this manner to estimate the average standard deviation in dimensional measurements from group to group and the average variation in true shrinkage from group to group. The results are presented in Table 4. The average standard deviation in measurements in four directions on 20 parts blown from each of 6 batches of bead stock was 0.0018 in.

When the true shrinkage was calculated on these parts in four directions, the average value was -0.0054 in/in and the standard deviation in the shrinkage measurement was 0.00022 in/in. Four standard deviations about a mean shrinkage value provide a 95% confidence limit of 0.00088 or about 0.001 in/in. Six standard deviations (99% confidence interval) would be 0.0012 in/in.

2.4.3.5 Foam Expansion and Contraction. A typical expansion and contraction curve on a group of 20 foam parts blown from bead batch A-02 is illustrated in Figure 19. The first data cluster represents shrinkage from the tool within about 5 minutes after production. The letters used to indicate the data points are A, B, L, W, and X corresponding to the A, B, L, W₁, and W₂ dimensions illustrated in Figure 18. A second set of measurements was made approximately 100 minutes after the foams were produced, and some pattern expansion had occurred by this time. The foam continued to expand slightly for about 400 minutes after production and then began to shrink. The foam progressively shrank in all five dimensions from approximately 400 minutes to 140,000 minutes after production.

The curves drawn through the data represent a third order, least squares, best fit line through data points of a particular dimension such as L, W₁, etc. The scatter within a particular dimension is a result of

Table 4.

Measurements and Standard Deviations and True
Shrinkage in 120 Patterns after Aging for 1.7 Weeks

	<u>Dimensional Measurements</u>		<u>True Shrinkage</u>	
	<u>Avg. Measurement</u>	<u>Avg. Std. Dev.</u>	<u>Avg. Shrinkage</u>	<u>Avg. Std. Dev.</u>
A	3.7336	0.0027	-0.0053	0.00022
B	3.7434	0.0010	-0.0052	0.00028
L	13.5310	0.0020	-0.0045	0.00014
W ₁	5.0726*	0.0036*	-0.0068*	0.00068*
W ₂	6.2201	0.0015	-0.0065	0.00024
<u>AVG.</u>		0.0018	-0.0054	0.00022

* The high standard deviation in the W₁ shrinkage appeared to be a result of an error in this dimension introduced when the largest gauge fixture was converted to the smallest gauge fixture.

616-203b

Figure 19. Foam Dimensional Changes Plotted in Logarithmic Time for Three Cylinder Lower Block Section Blown with ARCO EPS after Preexpanding to a Bulk Density of 1.6 pcf, Stabilizing for 2 Hours at 85°F, and Blowing. Pentane Content at the Time of Blowing was 6%. Batch Number A-02.

variations in foam dimensions and measurement errors. Each data group contains 100 data points on five dimensions from 20 parts.

There was some difference in shrinkage between the different directions in a part on the same foam. This may be a result of inaccuracies in the slide positions when the tool was measured, or of slightly different expansion and contraction characteristics in different foam directions because of variations in bead density, bead fill pattern, nonuniform shrinkage onto metal cores in the tool, or other variables.

The data illustrated in Figure 19 is replotted in Figure 20 using a linear time scale. The ability to discriminate between foam changes occurring in less than a week are lost in the linear time line, but changes occurring in the four to six week period (40,000-60,000 minutes) are more clearly represented. Dimension L, which is the block length, has approximately stabilized after six weeks although slight shrinkage is still occurring. All of the remaining foam dimensions continued to change for up to 100,000 minutes (ten weeks). The changing dimensions imply that foams should be made and used in a just-in-time manufacturing operation because the foams do not truly stabilize. Castings need to be produced in a consistent time interval to achieve the desired finished dimensions.

The coefficients of the least squares best fit lines were used to calculate shrinkage in each dimensions as a function of lapsed time after blowing. Typical results are presented in Table 5. This table contains true shrinkage data in foam set A-02 for times of one to eight weeks in one week intervals. Each column provides the true foam shrinkage as a function of lapsed time in each part direction. For example, in the "A" dimension, the true shrinkage was 0.0041 in/in after one week, 0.0054 in/in after two weeks, and progressively increased to 0.0087 in/in after eight weeks. Shrinkage in the "A" dimension between four and six weeks increased from 0.0069 to 0.0079 in/in.

The shrinkage in the "B" dimension was 0.0042 in/in after one week and increased to 0.0081 in/in after eight weeks. The shrinkage in the "L" dimension was 0.0035 in/in after one week and 0.0063 in/in after eight weeks. Shrinkage in the "W1" and "W2" dimensions were about 0.0055 in/in after one week and about 0.0090 in/in after eight weeks. In all cases the beads were shrinking throughout the aging period of up to eight weeks.

Beads preaged for longer periods of time did not initially expand as much as those preaged for short periods of time. However, after about a week, parts produced had approximately the same dimensions irrespective of the bead preaging time.

Preaging times from 2 to 48 hours had very little effect on part shrinkage after four weeks stabilization if four standard deviations in true shrinkage were used as criteria in significant effect. In all cases the "A" dimension shrinkage ranged from 0.0063 to 0.0067 in/in after four weeks. There was some additional shrinkage in the foams after six weeks, but the preaging time did not have a significant effect at the 95% confidence level.

The influence of the preaging time and part aging time on shrinkage in the bore to bore "A" dimension is illustrated in Figure 21. The horizontal

Figure 20. Foam Dimensional Changes Plotted in Linear Time for Three Cylinder Lower Block Section Blown with ARCO EPS after Preexpanding to a Bulk Density of 1.6 pcf, Stabilizing for 2 Hours at 85°F, and Blowing. Pentane Content at the Time of Blowing was 6%. Batch Number A-02.

Table 5.

Foam Shrinkage (True) from one to Eight Weeks for Three Cylinder Lower Block Section Blown with ARCO EPS after Preexpanding to a Bulk Density of 1.6 pcf, Stabilizing for 8 Hours at 85°F, and Blowing. Pentane Content at the Time of Blowing was 6%. Batch Number A-08.

True Shrinkage (in/in) in Foam Set A-02

Lapsed Time Minutes	Weeks	Shrinkage				
		A	B	L	W1	W2
10080	1	-0.0041	-0.0042	-0.0035	-0.0056	-0.0054
20160	2	-0.0054	-0.0052	-0.0045	-0.0068	-0.0065
30240	3	-0.0063	-0.0059	-0.0050	-0.0075	-0.0071
40320	4	-0.0069	-0.0065	-0.0054	-0.0080	-0.0077
50400	5	-0.0075	-0.0069	-0.0057	-0.0085	-0.0081
60480	6	-0.0079	-0.0074	-0.0060	-0.0088	-0.0085
70560	7	-0.0083	-0.0077	-0.0061	-0.0091	-0.0088
80640	8	-0.0087	-0.0081	-0.0063	-0.0094	-0.0091

Figure 21. True Shrinkage after 4, 6, and 8 Weeks in the "A" Dimension on a Lower Block Section Blown from ARCO T Beads. 1.6 pcf, 6% Pentane.

axis provides the bead preaging time prior to blowing. The "Y" axis provides the true shrinkage from the tool dimension after blowing. The data points connected by solid lines show the shrinkage in the "A" dimension after 4, 6, and 8 weeks. Bead preaging times of 24 to 48 hours slightly reduced the shrinkage compared to beads blown from 2 to 10 hours after preexpansion. Preaging for up to 48 hours increased the shrinkage from the tool dimension by about 0.001 in/in compared to parts blown after 2 to 10 hours aging time. Shrinkage increased in the "A" dimension by approximately 0.001 in/in for each 2 weeks aging of parts.

3. SAND FILL AND COMPACTION

The purpose of sand compaction is to assure that sand firmly supports the pattern and casting as metal is poured. The purpose of the sand fill and compaction studies was to determine the effects of the important compaction variables on sand densification.

Sand deposition by pluviation, through screens of various sizes and from various drop heights showed that maximum sand density can be achieved by free fall through a 10 mesh screen using drop heights of up to 34 inches. However, pluviated sand will not fill pattern cavities or flow under overhangs.

Compaction studies on laboratory scale flasks, using a unidirectional vibration table showed that maximum sand densities in cavities and under overhangs are achieved with vibrational amplitudes between 0.001 and 0.004 inches. Pluviation had little effect on sand densification when vibration was used to move sand into pattern cavities.

Compaction studies on a pilot line Omni-axis compactor with full size steel flasks showed that sand moved most freely within a few inches of the top free surface. Additional energy was required to unlock densified sand beneath the free surface to fill cavities. Bulk sand flow occurred from the top to the bottom of a flask unless the sand was progressively densified from bottom to top. Vertical and horizontal bulk sand movement was found to be the source of pattern deformation.

Pattern cavity fill rates were proportional to flask acceleration. Pattern orientation in the flask also had a large effect on cavity fill rate. Cavities could be filled more quickly with 2 inches of sand burden compared to 6 inches. Tailoring the fill cycle to the compaction cycle is of great importance.

In addition to these laboratory tests on filling and sand densification in pattern cavities, other studies were made on selected industrial compactors. One horizontal clamped flask compactor and two vertical unclamped flask compactors were examined. In two of these studies, unusual sand acceleration values were obtained when the flasks were mapped, and were found to be related to worn impact pads and flasks that were no longer level.

Flask vibration is disturbed by actions of sand inside flasks even when flasks are clamped to the table. Studies on both bench scale and commercial flasks showed that the sand impacted the flask walls and interfered with the input excitation. Sand was also found to act somewhat independently of the flask. Bulk sand flow usually occurred upward along the flask centerline and downward at the flask walls. This motion was found in both vertical and horizontal compactors and had previously been attributed to an "oil can" effect, wherein the bottom of the flask acted as a diaphragm pump. However, the reason for sand flow up the centerline was the impacting of compression waves at the flask centerline.

Typical commercial flasks have natural frequencies above 1000 Hz in the vertical direction and 200 to 300 Hz in the horizontal direction. High natural frequencies imply high stiffness. The lower horizontal frequency implies that when flasks are vibrated, either by impact or by sine wave

excitation, they deform symmetrically side to side more than vertically. The symmetrical wall deformation introduces compression waves from opposite flask walls that meet near the flask center. As the compression waves meet, the impact energy is dissipated by accelerating sand grains vertically. The principal path of least resistance is upwards toward the free surface.

Consistent flask deformations were found in bench scale flasks, pilot line flasks, and the industrial flasks when the input accelerations were either impact events or sine waves. The flask sides always acted as diaphragms 180° out of phase. Opposite flask sides moved simultaneously either inward or outward. Walls 90° from the reference walls were 180° out of phase (i.e., when the first wall moved inward, the 90° wall moved outward). This motion was repeated with the perpendicular wall moving inward while the initial wall moved outward. Hence, sand motion was always inward toward the center.

Prior to sand densification, a flask impact in any direction causes the flask walls to vibrate at a value near its natural frequency. After densification, when the sand was more rigid, the flask vibrations were reduced to those of the table, irrespective of whether the driver was a series of sine waves or impact events.

Sand densification occurred in the first few seconds of vibration after filling. The time required for the densification was a function of the vibrational amplitude. Maximum sand density was achieved most rapidly with amplitudes of sand movement in the range of 0.001 to 0.004 inches. Once densification was complete and sand grains locked up, extra energy was required to cause sand movement for filling internal pattern cavities. The vibrational intensity was usually dictated by a production cycle of 60 to 100 seconds.

An efficient vertical compactor should produce acceleration of 4 G at frequencies of 200 Hz and above in the flask. The vibrational amplitude produced by 4 Gs at 200 Hz is about 0.001 inches which is adequate for densification. Achieving 4 G acceleration at 200 Hz with present vertical compactor designs comes at the expense of an unwanted higher accelerations at lower frequencies. Current motor speeds operate up to 6000 RPM (100 Hz) for short periods of time. More practical motor speeds of 3600 RPM (60 Hz) are used to extend motor life. This 60 Hz vibration is always detectable directly above each support pedestal and usually produces the highest acceleration in the frequency spectrum. The higher frequencies are produced by repeated pedestal impacts (bouncing) but are usually lower in amplitude than the fundamental drive amplitude. Unclamped vertical compactors produce not only vertical vibrations but also horizontal vibrations. This combination provides a complex vibration in the sand which has dictated trial and error development of compaction cycles.

An efficient horizontal compactor should operate at 2 to 4 Gs at frequencies between 50 Hz and 400 Hz for minimum fill time, but these combinations generate excessive sand pressures with one exception - 2 Gs at frequencies of 50 Hz to 200 Hz. Amplitudes of vibration for these frequencies show that only 100 Hz would provide sand densification. Current horizontal compactors operate at frequencies below 60 Hz.

4. GATING, POURING, AND MOLD FILLING

4.1 Introduction

Once the pattern is compacted in sand, the flask is ready to be poured. Pouring, pattern recession, and mold filling are important aspects associated with producing quality metal castings free of internal defects. Gating of EP castings is critical to the process but unfortunately requires experience and a trial and error approach. Once a proper gating system has been determined using gates cut from foam boards, the foam gating systems are usually molded and, if possible, become an integral part of the pattern to minimize the number of glue joints and the possibility of coating erosion. It is important to keep in-gates robust because flimsy and delicate gates can be damaged or broken during handling and compacting.

The goal of pouring is to fill the mold with metal in the least turbulent fashion to minimize metal oxidation, laps, and fold defects. Many types of in-gates are successfully used on particular castings including top, bottom, pencil, knife, and horn gates.

Metal must be poured into EPC molds at a rate that equals the pyrolysis rate of the pattern. Slow or intermittent pouring almost always results in catastrophic mold collapse. Sufficient metal must be present, and the static head pressure must be maintained during pouring to prevent mold collapse into the gap between the advancing metal front and the retreating foam pattern. The affinity of iron and aluminum for oxygen, and the ability of these metals to entrain gases, makes pouring control critical for success.

Foamed patterns undergo degradation during pouring by a series of transitions involving foam collapse, melting, depolymerization, pyrolysis, and evolution of gaseous-polymer fragments. The presence of degradation products in the mold cavity may lead to defects in castings including gas bubbles, porosity in aluminum, carbon defects in cast iron, and carburization of steel.

Pouring must not only minimize entraining air and sand but must avoid entraining residue from the pattern. Minimizing the capture of residue depends on gate design, pouring rate, pattern geometry (especially the ratio of surface area to volume), coating and sand permeability, flask venting, foam density, foam type and the use of vacuum.

Molds using unbonded sand are more delicate than conventional sand casting molds. The advancing liquid metal front must support the unbonded sand and coating while allowing the foam pyrolysis products to escape. If gating and pouring are not correct, scrap castings will be the result. For example, if the pouring operation is interrupted, the metal will not only stop advancing but may retreat. This exposes an unsupported sand and coating wall which can collapse into the gap between the solid foam and molten metal. If pouring is too fast, decomposition gases create high local pressures and fluidize the sand, resulting in a loss of sand support for the ceramic coating. The result is a ruptured mold coating and metal penetration into the sand.

The main purpose of the gating system is to deliver liquid metal to the mold cavity. This must be done without unacceptable degradation of either the

mold or metal. The gating system is also used to help establish the desired thermal gradients and provide feed metal to promote casting soundness. In this process, the gating system must direct metal flow to support the mold cavity while allowing the pyrolysis products to escape. The gating system is also commonly used to support the cluster during handling, coating, sand fill, and compaction. The gating system must be strong and stiff enough to allow handling and possibly stiffen some pattern areas to minimize distortion.

A large pouring basin is normally used to provide a continuous molten metal source with adequate liquid metal head pressure. The basin is usually made from bonded sand, molded fiber products, or ceramic to prevent collapse during pouring. The metal head pressure must exceed the pressure at the metal-foam interface or spitback will occur. Hollow sprues and bottom gates help insure that the metal head pressure is adequate to avoid spitback. Higher metal head pressures generally result in better castings. Hollow sprues and hollow gating system components can be used with aluminum to help direct metal flow into the casting cavity.

The frequency of surface carbon defects is lower with top or side gating in iron castings production, but internal carbon defects are often present as a result of entrained foam residue. Bottom gating reduces the incidence of internal carbon defects but results in carbon defects on the cope surface, especially above thick sections. For this reason, it is common to orient thicker parts vertically rather than horizontally. Castings with wall thicknesses of 1/8-1/4 inch do not normally present problems, but thicker walls may need more gate connections, lower density foams, alternate foam materials, different coating formulations, vacuum during pouring, or other adjustments to minimize carbon defects.

Care must be taken in designing gating systems to minimize the occurrence of streams of liquid metal meeting within the casting cavity. Some pattern residue is carried on the leading edge of flowing metal streams, and when two streams meet, residue is often trapped at or near the line of contact. Abrupt changes in section size should also be avoided for this reason. Gating systems must be designed recognizing that metal stream fronts accumulate residue, and this material must be absorbed by the coating or expelled into a riser or pop off.

Foam pyrolysis is not as rapid when pouring aluminum, and the pouring rate is lower compared to iron pouring practices. For this reason, larger gates and sprues are needed. Laps and folds in aluminum castings are the result of a combination of entrapped residue and inadequate metal thermal energy to complete fusion and bonding when metal streams meet.

Bottom gating gives the gating engineer the most control over filling the mold cavity. The metal falls in the most controlled way into the sprue and rises in a regular fashion in the mold cavity. The advancing metal front supports the sand wall while allowing decomposition products to escape into the casting along the gap between the retreating foam and the advancing metal front.

A vacuum is sometimes applied to a flask during pouring. The vacuum pulls gases from the flask, prevents sand fluidization, and improves filling

of thin casting walls. The vacuum system can also be used to collect pyrolysis products produced during pouring.

EP castings are normally poured as rapidly as allowed by the retreating foam pattern. Automatic ladle pouring is commonly used to assure consistent pouring rates. This minimizes the number of people in the pouring area, reduces variations in the rate of pouring, and allows controlled adjustments to be made of the pouring operation.

4.2 Pattern Pyrolysis During Pouring

Polystyrene melts at about 465°F (240°C), begins to volatilize at about 700°F (315 °C), burns at 1060°F (576°C), and given sufficient time, decomposes into hydrogen and carbon. One mole of polystyrene (104 grams) produces about 1,000 liters of gas if completely combusted at 1000°C and one atmosphere pressure. However, when iron is poured into a mold at 2500°F, the heating rate is so rapid that the polystyrene melts, produces some vapors, and partially gasifies without complete combustion.

Polystyrene decomposes by random scission which initially produces liquids. When the liquids are exposed to high temperatures, the benzene rings break, leading to some carbon and char formation. The temperatures encountered in producing aluminum castings are not sufficiently high to break all benzene rings to produce elemental carbon, and few carbon problems occur when pouring this metal. But high molecular weight liquid polymers do accumulate on liquid aluminum metal fronts and cause surface defects on cope surfaces and where the metal fronts meet.

More gases are generated during the initial phases of metal pouring when EPMMA patterns are used because of the immediate decomposition of the pattern into gaseous products. Methods of overcoming the higher gas volumes include the use of more permeable refractory coatings, a vacuum on the flask, hollow sprues, and the use of EPS sprues.

Some of the pyrolysis products are absorbed into the ceramic coating where additional decomposition can occur after passage of the metal front. Several characteristics including the surface tension of the liquid, the capillarity of the coating, the geometry of the casting, and the composition of the foam, influence absorption by the coating.

4.3 Preliminary Pyrolysis Experiments

Several bench scale experiments were conducted to obtain preliminary information on the events occurring as foam is heated.

Thermogravimetric analyses (TGA) of several foam materials are illustrated in Figures 22 through 24. The results when heating unexpanded polystyrene T beads in nitrogen at a rate of approximately 36°F per minute are shown in Figure 22. The unexpanded T beads were unaffected until a temperature of approximately 250°F was reached, at which point the expanding agent began to diffuse out. The expanding agent was lost over the temperature range of 250°F to 300°F. The bead material held a constant weight of approximately 96% of the original weight until it reached a temperature of approximately 700°F, at which point the weight dropped steadily until at

Figure 22. TGA Curves for Unexpanded Polystyrene T Beads Samples Heated at a Rate of 36°F/min (20°C/min) in Nitrogen.

Figure 23. TGA Curve for EPS Sample Heated at a Rate of 36°F/min (20°C/min) in Air.

Figure 24. TGA Curves for EPMMA Samples Heated at a Rate of 36°F/min (20°C/min) in air

a temperature of approximately 880°F, only 0.1% of the original material remained.

Similar results on expanded polystyrene heated in the air are illustrated in Figure 23. The expanded polystyrene had already lost the pentane expanding agent so heating occurred to a temperature of approximately 550°F before significant decomposition and weight loss began. Decomposition and weight loss occurred rather quickly over the range of approximately 600-840°F.

TGA curves and data obtained on duplicate samples of expanded PMMA are illustrated in Figure 24. A weight loss of approximately 10% occurred over the temperature range of 265-340°F, after which the weight remained relatively constant until the material reached approximately 550°F. Most of the remaining material was lost over the temperature interval from 600-800°F.

These results, obtained under controlled heating conditions at a constant heating rate of 36°F per minute, indicate that polystyrene has the highest decomposition temperature range of approximately 700-860°F followed by PMMA which decomposed over the range of approximately 300-800°F.

4.4 Model for Mold Filling in Aluminum

A physical model for foam pattern replacement and mold filling in the EPC process has been developed for aluminum and applied to cast iron. The model is illustrated in Figure 25. The following steps describe how the foam decomposition products are, under somewhat idealized conditions, transferred from the pattern into the sand.

Step 1: The heat of the liquid metal causes the foam to collapse, soften, melt, and eventually decompose into smaller molecules including gases. Approximately 96% of the original foam volume is initially air, which is released during foam decomposition.

Step 2: The melted polymer, air and gaseous decomposition products from the foam are pushed aside by the molten metal and collect at the interface between the metal, foam, and ceramic coating. If these products are not pushed to the metal-coating interface, but instead are carried along with the metal front, casting defects may be formed.

Step 3: The air and gaseous decomposition products that collect at the metal-foam-coating interface escape through the coating and into the sand along a "gap". The length of this gap is the perimeter of the casting at the metal-foam-coating interface. The true thickness of the gap is not known. If the transfer of mold gases through the coating is too slow, a gas back pressure can develop, which slows the front velocity and can cause incomplete filling, or misruns.

Step 4: When the liquid polymer and the coating reach a critical temperature, the polymer wets the coating surface. If wetting does not occur, the thickness of the liquid polymer may be nonuniform and may cause surface defects on the casting.

Step 5: When the liquid polymer and the coating reach a higher critical temperature, the polymer wicks into, or infiltrates the coating. If wicking

Figure 25. Physical Model for Mold Filling in EPC Castings.

into the coating does not occur, the polymer may cause surface defects on the casting.

Step 6: As the coating continues to heat, most of the absorbed polymer liquid decomposes to form gases which escape into the unbonded sand. Some small portion of the polymer may carbonize and remain in the coating.

Step 7: Some polymer decomposition products condense in the cooler sand around the pattern. However, as the "heat wave" from the casting moves into the sand, the condensed products are revaporized and pushed further from the metal-mold interface. The physical properties, including molecular weight, composition, and boiling temperature of the decomposition products change during this process.

The key to assuring complete mold filling while minimizing casting defects lies in removing the foam decomposition products at an optimum rate. If the decomposition products are removed too quickly, the back pressure offered to the liquid metal front is low; the metal-foam interface is no longer smooth; metal flow becomes turbulent; and the decomposition products are trapped in the casting which leads to internal defects.

If the decomposition products are removed too slowly, pyrolysis products may be trapped at the metal-coating interface and produce surface defects. If the decomposition products are not removed quickly enough from the interface between two metal fronts and the coating, laps and folds are formed.

Several casting parameters influence the amount and nature of the foam decomposition products that must be eliminated from the casting cavity, and the rate at which the products can be transferred. These parameters include the properties of the foam, the size and geometry of the pattern, the properties of the refractory coating, the properties of the molding sand, the composition of the casting alloy, the design of the gating system, pouring temperature (or superheat), and the metallostatic head. The remainder of this section describes the effects of these casting parameters on filling molds with cast aluminum and iron.

4.4.1 Patterns. Pattern decomposition is the first step in the mold filling process. The nature of the pattern material and the ease with which it melts and decomposes has a large influence on the filling process.

Liquid metal must displace the foam pattern, and the decomposition products must exit from the casting cavity in the EPC process. Consequently, the ability of the liquid metal to fill the mold depends on both heat transfer and mass transfer. The rate of heat transfer is related to the volume-to-surface area ratio of the pattern, and patterns with large volume-to-surface area ratios fill more completely.

Mass transfer of liquid and gaseous decomposition products, however, depends on the volume and nature of the decomposition products and on how rapidly these products can be removed from the metal-foam-coating interface. The rate of mass transfer depends to a large extent on the coating surface area exposed to the gases. The surface area is the product of the perimeter of the pattern at the metal-foam-coating interface and the width of the "gap"

at this interface. If the width of the gap is assumed to be relatively constant, the mass transport is related to the metal front perimeter. For a given pattern volume-to-surface area (i.e. constant heat transfer), a larger perimeter should provide easier mass transfer and consequently improved casting fillability.

4.4.2 Coatings. While the characteristics of the foam help determine the volume and nature of the decomposition products that must be removed, the properties of the refractory coating are crucial for determining the rate at which the products can be transferred from the casting cavity. The liquid polymer must wet and eventually wick into the coating, while air and gaseous decomposition products must diffuse through the coating to escape the metal front. These factors depend to a great extent on the permeability of the coating.

When two coatings of similar permeability were applied the fillability was better with the coating producing a thicker layer. This phenomena was attributed to the thermal insulation provided by thicker coatings, which reduced the heat transfer rate from the molten metal. When coatings of a similar coating thickness were used, the fillability was better with the coating producing a higher permeability. The higher permeability produced a higher mass transfer. These observations suggest that it might be possible to tailor a coating to a particular filling problem produced by particular heat or mass transfer limitations.

The coating must also allow wetting and infiltration of melted polymer. A critical combination of liquid polymer and refractory coating temperature was required for liquid polystyrene to wet the coating, as shown by the data in Figures 26 through 28. Wetting occurred most easily in a high permeability alumina coating, less easily in the mica coating, and least easily in the low permeability silica coating at room temperature. Wetting occurred in all three coatings at 200°C.

Higher critical temperatures were required for infiltration of liquid polystyrene into coatings. For liquid polystyrene heated to 300°C, a coating temperature of 450°C was required for infiltration to begin in the high permeability alumina coating, 525°C in the mica coating, and nearly 600°C in the silica coating.

The rate of infiltration depended on the coating temperature and the type of coating. The depth to which the polystyrene infiltrated increased with the square root of time, as expected in a process driven by capillary filling. The rate increased with increasing temperature and with increasing coating permeability, as shown by the data in Figure 29.

Commercial coatings are typically on the order of 0.008 inch (0.2 mm) thick. Based on these results, wetting and infiltration through a 0.008 inch thick high permeability alumina coating should occur almost instantly. However, significantly longer times (even longer than the fill time for the casting) were required to completely infiltrate mica and silica coatings with liquid polystyrene. Liquid PMMA was found to behave similarly to liquid polystyrene.

DA17

Figure 26. Effects of Molten Polymer Temperature and Coating Temperature on Polymer Wicking and Wetting in High Permeability Coating.

DA18

Figure 27. Effects of Molten Polymer Temperature and Coating Temperature on Polymer Wicking and Wetting in Low Permeability Silica Coating.

DA19

Figure 28. Effects of Molten Polymer Temperature and Coating Temperature on Polymer Wicking and Wetting in Low Permeability Mica Coating.

DA20

Figure 29. Effect of Infiltration Time on Coating Penetration Depth.

Unless the Baumé of a slurry was appropriately adjusted, increasing the thickness of a coating reduced the permeability. A lower permeability reduced the metal fillability with other conditions held constant.

These results suggested that, for aluminum, permeability of the coating (as influenced by coating thickness) is critical in determining metal velocity and fill time. However, perhaps due to the lower pouring temperature and the smaller temperature gradient between the liquid and the mold, doubling the fill time or reducing the metal velocity by a third did not appreciably affect the heat transfer rate, thus causing a relatively small decrease in fillability.

Permeability did not appear to be a big factor affecting the fill time for cast iron. This difference was probably due to the differing nature of the decomposition products. At the cast iron pouring temperature, the foam rapidly and nearly completely decomposed to gaseous products, which flowed through the coating. When aluminum was poured, less gases and more liquid products were formed, and transfer of the mass through the coating was slower.

These observations suggest that a thick coating might provide an insulating effect in aluminum, so even if a thick coating reduced metal velocity and increased fill time, the lower rate of heat transfer might provide good (or even improved) fillability. However, in cast iron, thicker coatings evaluated to date have not provided sufficient insulation to overcome the effects of permeability and orientation.

4.4.3 Metallostatic Pressure. Increasing the metallostatic pressure can be expected to increase metal velocities and improve fillability, from traditional fluid flow considerations and because higher metal pressures may help force gaseous decomposition products through the coating. Figures 30 and 31 illustrate these results. Thin section castings were poured with aluminum and iron in two orientations. Some castings were poured vertically with the gate at the bottom, which produced a decreasing metal head pressure during filling. Others were poured horizontally, thus maintaining a high and relatively constant pressure head. Patterns with a horizontal orientation produced higher metal velocities and more complete filling using a coating with a constant permeability (when pouring either aluminum or iron). In fact, the higher metal pressure produced by changing the orientation of the pattern was sufficient to offset the coating permeability effect when pouring cast iron.

Based on current concepts for mold filling, gate area was not expected to be an important factor in controlling metal velocity, fill time, or fillability. In conventional casting processes, a choke in the gating system controls metal flow. In the EPC process, the "choke" in the system is the rate at which the foam can be displaced and the decomposition products removed from the metal-coating interface. Unless the gate area is abnormally small, liquid metal can pass through the gate more rapidly than foam can be decomposed or the decomposition products can be transferred through the coating.

4.4.4 Decomposition Products in the Coating and Sand. The decomposition products from the foam are transferred into the coating and then into the

DA27

Figure 30. Effect of Metal Temperature Coating Permeability and Pattern Orientation on Aluminum Casting Fillability.

DA28

Figure 31. Effect of Metal Temperature Coating Permeability and Pattern Orientation from Casting Fillability.

surrounding sand. Several features of the transfer process, however, limit the extent to which the decomposition products can be eliminated. First, some of the decomposition products may heat to a high enough temperature that carbonization occurs. This helps to "fix" the pyrolysis products in the coating or sand. Second, the sand is initially hot and the rate of heat transfer into the sand is lower than the rate at which gaseous decomposition products move into the sand. Consequently gases with a boiling temperature below the sand temperature may condense. Although the condensate may later revaporize and move further into the sand, some of the condensate may also carbonize. As a result of these reactions, the composition of the coating and sand may continually change.

4.5 Casting Defects in Aluminum-Silicon Alloys

Some implications of the physical model for mold filling on the origin and severity of casting defects were tested by pouring a series of aluminum-silicon alloy castings. Silicon contents were varied from about 6% (hypoeutectic) to 15% (hypereutectic). A 1.2 in. diameter EPS bar was poured using different gating systems, pouring temperatures, and alloy composition. Three types of defects - surface depressions (orange-peel defect or alligator skin), laps (produced when two metal streams met), and internal porosity - were examined.

4.5.1 Silicon Concentration Effects. Although higher silicon concentrations did not significantly affect internal porosity, they did cause more severe surface and lap defects. The high silicon alloys resulted in higher metal velocities (less time for wicking of liquid polystyrene) and produced a less symmetrical metal front (permitting a greater concentration of liquid polystyrene at the top surface of the casting).

4.5.2 Pattern Geometry Effects. The round bar used in these tests had a relatively small perimeter for its volume-to-surface area ratio. The small perimeter made it difficult to remove decomposition products from the metal-foam-coating interface, and increased the likelihood of casting defects. A 0.5 in. x 4 in. plate, oriented so that the 4 in. dimension was vertical, was poured to test this concept. The top surface of the metal front trailed the bottom surface in this casting by nearly two inches. However, because of the large perimeter compared to the round bar, no surface defects were produced.

5. CASTING PRECISION AND ACCURACY

The objective of this portion of the study was to determine the dimensional accuracy and precision of iron and aluminum castings produced using green sand, no-bake, and EP casting techniques. The highest quality patterns were used in all cases. All patterns were NC machined from 6061 aluminum billets and the patterns were carefully checked for accuracy after machining.

5.1 Test Patterns

The dimensions of the patterns used in this study are illustrated in Figures 8 and 9. A variation on this pattern has been shown to be useful in evaluating effects of process variables on casting precision. Foam shrinkage values of 0.8% for EPS and 0.25% for EPMMA combined with 1% metal shrinkage from the foam dimension were used to calculate the expected casting dimensions.

The only differences between the EPC test cone in Figure 8 and the sand cast cone in Figure 9 are the four 6-mm-diameter cast-in holes on the flange and the 12-mm-diameter center hole on the top of the EPC pattern. Both the match plate and the cope and drag patterns were machined to produce this casting. A shrinkage of 1% from pattern dimensions was assumed for the conventional casting processes.

Ovality ("O") or out-of-roundness of test castings was also determined for the "A", "B", and "C" dimensions. Ovality was determined by subtracting the 0° to 180° diameter (centerline distance at 0° + centerline distance at 180°) from the 90° to 270° diameter (centerline distance at 90° + centerline distance at 270°) and squaring the resulting number. The number was then averaged for each dimension and the square root calculated as shown in Eq. 3.

$$O = \sqrt{(\sum (D_{(0-180)} - D_{(90-270)})^2) / n} \quad (\text{Eq. 3})$$

where n = number of castings

5.2 Statistical Analysis

Casting precision refers to the degree of repeatability, exactness, or consistency among a large number of identical measurements. The sample standard deviation in a series of measurements was used in this study as an indication of the degree of precision. A precision norm (PN) was calculated for each group of dimensions. The precision norm is the square root of the variance of the individual precision values and is defined in Equation 4.

$$PN = \sqrt{P_A^2 + P_B^2 + P_C^2 + P_H^2} \quad (\text{Eq. 4})$$

where

PN	-	Precision Norm
P_A	-	Sample standard deviation of the "A" dimension values
P_B	-	Sample standard deviation of the "B" dimension values
P_C	-	Sample standard deviation of the "C" dimension values
P_H	-	Sample standard deviation of the "H" dimension values

Each of the individual precision components, ie., P_A , P_B , P_C etc., was calculated using Equation 5.

$$P = SD = \sqrt{\Sigma(y - \bar{y})^2 / (n-1)} \quad (\text{Eq. 5})$$

where

P	-	Precision deviation
SD	-	Standard deviation
y	-	Measured value
$\bar{y}$	-	Average of measured values
n	-	Number of observations

The coefficient of variation is the ratio of the standard deviation in a sample expressed as a percentage of the arithmetic mean value of the sample. The coefficient of variation (CV%) allows variations among groups of data with different arithmetic means to be compared.

Accuracy has been defined as the agreement between the mean of a series of repeated measurements of a dimension and an accepted reference value of the dimension. For the matchplate and the cope and drag patterns, the reference value for each dimension was determined by subtracting 1% for metal contraction from the pattern dimension.

A foam shrinkage of 0.8% for EPS and 0.25% for EPMMA plus 1.0% for metal shrinkage was subtracted from the tool dimension to provide the expected casting dimensions. An accuracy norm (AN) was calculated for each group of dimensions. The accuracy norm was the square root of the variance of the individual accuracy values and is defined in Equation 6.

$$AN = \sqrt{A_A^2 + A_B^2 + A_C^2 + A_H^2} \quad (\text{Eq. 6})$$

where

AN	-	Accuracy norm
A_A	-	Accuracy of the "A" dimension values
A_B	-	Accuracy of the "B" dimension values
A_C	-	Accuracy of the "C" dimension values
A_H	-	Accuracy of the "H" dimension values

The accuracy for each individual component, ie. A_A , A_B , A_C , etc., was calculated by subtracting the calculated reference value from the mean of the measured values for each dimension using Equation 7.

$$A_i = \bar{y} - y_p \quad (\text{Eq. 7})$$

where

A_i	-	Accuracy for dimensional component "i"
$\bar{y}$	-	Average of measured values
y_p	-	Predicted y value

5.3 Dimensional Analysis Results

All but one set of laboratory castings considered in this study were produced in commercial foundries. Some were produced from the match plate pattern, others from the cope and drag pattern, and still others from EP foam patterns. All EP aluminum castings were produced from EPS foams with a density of 1.6 pcf. Iron castings were produced from EPS at a density of

1.3 pcf or EPMMA with a density of 1.5 pcf. Mold coatings and compaction cycles were based on foundry experience.

5.3.1 Aluminum Casting Results. The precision norm for the "A", "B", "C", and "H" dimensions on aluminum castings made by EP and conventional casting methods is illustrated in Figure 32. Three sets of EP castings produced by Foundries AC4 and AC3 were more precise than the conventionally cast test cones. One set of EP castings produced by AB9 was less precise than the conventionally cast test cones. This set of castings had been shot blasted which produced a rougher surface that may have decreased the coating precision.

The ovality data on EP and conventional cast test cones is illustrated in Figure 33. All four sets of EP castings were more round (less oval) than the conventionally cast test cones.

The accuracy norm calculated from the "A", "B", "C", and "H" dimensions on aluminum castings made by EP and conventional methods is illustrated in Figure 34. The EP aluminum castings were slightly less accurate than the conventionally cast test cones. Most of the inaccuracies measured in the EP were in the "C" and "H" dimensions. While the EP castings are less accurate, the accuracy norm only varied 0.008 inches over the four sets of castings. The inaccuracies were a result of unexpected foam shrinkage values which could be caused by variations in foam density in the patterns. These inaccuracies can be reduced by slight tool adjustments.

Typical aluminum EP castings are illustrated in Figure 35. The ability to achieve good casting detail and cast holes makes EP castings commercially attractive.

5.3.2 Iron Casting Results. Most of the cast iron test cones were poured in the early stages of this project. As more information was gathered on the effect of the compaction cycle on fill and pattern distortion, it became evident that compacting the backup sand at low energy levels could be used to minimize pattern distortion.

The precision norm of the "A", "B", "C", and "H" dimensions on iron castings made by EP and conventional casting methods is illustrated in Figure 36. With two exceptions, the EP iron castings were less precise than conventional castings. The complicated and lengthy compaction cycles initially used to produce the EP casting resulted in lower precision. The small set of EP castings (AC12) with the best precision of any group of EP castings was produced with PX-677 coating. This was the only difference between these test cones and other test cones from Foundry AC1 (AC11, AC13, AC14). The most recent set of EP test cones cast (AC15) had a precision norm comparable to conventionally cast cones.

Based on compaction principles developed in the project, the set of foam patterns were compacted at low acceleration levels ($\leq 1 G$). The patterns (AC15) were backed with 29 GFN subangular sand. The eighteen gray iron castings had an "A", "B", "C" and "H" casting precision of 0.025, 0.013, 0.007, 0.019 inches, respectively, and an average surface finish of

Figure 32. Precision Norm for the "A", "B", "C", and "H" Dimensions on Conventional and EP Aluminum Castings.

Figure 33. Ovality of Conventional and EP Aluminum Test Cones.

Figure 34. Accuracy Norm for the "A", "B", "C", and "H" Dimensions on Conventional and EP Castings.

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Figure 35. Typical Aluminum Test Casting Made from EPS Patterns. (a) Top View and (b) Bottom of Casting

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Figure 36. Precision Norm for the "A", "B", "C", and "H" Dimensions on Conventional and EP Castings.

528 microinches. The precision norm was 0.035 inch and casting ovality was 0.014 inch.

The ovality of iron castings made by EP and conventional methods is illustrated in Figure 37. With the exception of one small group of EP castings (AC1-3), the EP casting ovality measurements were as good or better than the ovality of the sand castings.

Dimensional accuracy data on EP and conventionally cast test cone dimensions "A", "B", "C", and "H" are illustrated in Figure 38. A set of EP test castings produced with a low impact compaction cycle in Foundry AC15 were the most accurate. A set of no-bake cast test cones (AB5) were the next most accurate castings. They were followed by a set of green sand cast test cones (AE8) and all three sets of 1.3 EPS cast test cones. The 1.5 EPMMA test cones were usually less accurate than the 1.3 EPS test cones. The inaccuracies associated with some of the EP castings may have been due to variations in foam shrinkage from the assumed value of 0.8%. The EP patterns compacted at a low energy level at Foundry AC15 improved dramatically in accuracy compared to patterns compacted at higher energy levels.

A typical EP cast iron part is illustrated in Figure 39. The surface finish of this part was 410 microinches with a standard deviation of 79 microinches. The EP cast parts usually had a better surface finish than the sand cast parts.

5.4 Summary of Dimensional Results

A cone pattern was used to determine the dimensional precision of EP and conventional sand castings. All conventional sand casting processes had difficulty with the 0.5° taper on the pattern. After much difficulty drawing the pattern from sand molds, the cope and drag pattern taper was increased to 1°. None of the conventional sand casting processes could produce cast-in holes on the flange or top of the cone casting.

EP foam patterns compacted using low energy levels produced the most accurate castings. Green sand cast test cones were generally less accurate than the EP test cones.

It was concluded from these dimensional analyses that EP castings can be produced with high dimensional precision and accuracy, but not necessarily better precision than sand castings made from high quality, precisely machined patterns. Care must be taken in the sprue arrangement and compaction to minimize pattern distortion. Compaction energy levels have a significant effect on casting precision and accuracy, with lower energy compaction cycles producing higher precision castings.

Figure 37. Ovality of Conventional and EP Cast Iron Cones.

Figure 38. Accuracy Norms for the "A", "B", "C", and "H" Dimensions on Conventional and EP Cast Iron Cones.

(a)

(b)

615-758

Figure 39. Typical EP Foam Cast Gray Iron Casting. (a) Top View and (b) Bottom View.

6. PHYSICAL PROPERTIES OF EP DUCTILE IRON

Before EP castings can be widely used, sufficient data must be developed to give designers and engineers confidence in allowable static and dynamic design stresses. This portion of the program was undertaken to develop a limited data package on EP ductile iron tensile and fatigue properties compared with conventionally cast ductile iron.

6.1 60-45-12 Ductile Iron Tensile Properties

Three sets of test bars were poured from a single ladle of 60-45-12 ductile iron. The test bars were poured using 1.2" diameter EPS pcf patterns, 1.2" diameter pcf PMMA patterns, and keel block molds. Some of the EP foam patterns were sealed with an acrylate prior to applying the refractory layer. The chemical composition of the 60-45-12 ductile iron poured was as follows; 3.80% carbon, 2.24% silicon, 0.33% manganese, 0.011% sulfur, 0.017% phosphorus, 0.038% chromium, 0.012% nickel, 0.008% molybdenum, 0.079% copper, and 0.054% magnesium.

The bars were blanked to a right cylinder 0.025 inches longer and 0.015 inches larger in diameter for nondestructive testing (NDT). A section of each bar was also removed for hardness measurements. The blanked specimens were tested to determine the density and ultrasonic transmission velocity. After the nondestructive evaluation, 0.505 threaded tensile specimens were machined to the final configuration.

A composite of the stress-strain curves of all specimens cast on EPS and PMMA patterns is illustrated in Figure 40. The curves overlapped up to the strain limit illustrated.

A composite of stress-strain curves from the EPS castings, PMMA castings and the keel blocks is illustrated in Figure 41. Again, all the stress-strain curves fell within a narrow band.

Nondestructive characterization test results, hardness, and tensile data on the 60-45-12 ductile iron cast is presented in Table 6. This table lists entry number, specimen number, NDC results, 0.2% offset yield strength, ultimate strength, and elastic modulus.

The average density of the EPC bars was 7.037 g/cc in EPS and 7.042 in PMMA, values very close to that obtained from the keel mold cast bars at 7.0350 g/cc. The average ultrasonic modulus of both sets of bars were also close with 25.96 mpsi in 1.4 EPS bars, 25.95 mpsi in PMMA bars, and 25.77 mpsi from the keel blocks. Average hardness was comparable for all bars with 175 Bhn on the 1.4 EPS bars, 170 Bhn in PMMA bars, and 161 Bhn in the keel block legs. The lower keel block hardness was a result of the lower solidification and cooling rate in the heavy section keel block.

Yield strength values were 47.6 ksi in the 1.4 EPS castings, 47.9 ksi in PMMA castings, and 48.5 ksi in keel blocks. The average ultimate strength values were 74 ksi in EPS bars, 77 ksi in PMMA bars, and 73.5 ksi in the keel block legs.

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Figure 40. Composite Plot of Tensile Stress-Strain Curves for 1.4 pcf EPS and 1.5 pcf EPMMA Cast Ductile Iron Bars.

Figure 41. Composite Plot of Tensile Stress-Strain Curves for 1.4 pcf EPS, 1.5 pcf PMMA, and Keel Block Cast Ductile Iron Bars.

Table 6.

**NDC, Hardness, and Tensile Data on 1.4 EPS, 1.5 EPMMA, and
Keel Block Cast 60-45-12 Ductile Iron. (Threaded 0.505" Dia Specimens)**

Entry Number	Specimen Type	Specimen Number	Mold Type	Bulk Density (g/cc)	Ultrasonic Velocity (in/usec)	Ultrasonic Modulus (mpsi)	Hardness (BHN)	0.2% Offset Yield (ksi)	Ultimate Strength (ksi)	Modulus (extensomer) (mpsi)	Strain At Failure (%)	Area Reduction (%)
1	Tensile	DI0047	1.4 EPS	7.0298	0.2245	25.94	158	47.2	76.2	24.16	2.26	8.71
2	Tensile	DI0048	1.4 EPS	7.0409	0.2246	26.00	207	47.6	75.9	25.36	5.90	4.39
3	Tensile	DI0049	1.4 EPS	7.0383	0.2246	25.99	170	47.9	75.1	25.16	5.12	4.23
4	Tensile	DI0050	1.4 EPS	7.0377	0.2242	25.90	163	47.7	72.1	24.58	3.86	2.87
Average =				7.0367	0.2245	25.96	175	47.6	74.8	24.82	4.29	5.05
Std. Dev. =				0.0048	0.0002	0.05	22	0.3	1.9	0.55	1.59	2.53
9	Tensile	DI0051	1.5 EPMMA	7.0332	0.2246	25.97	156	46.7	75.1	24.21	6.60	6.89
10	Tensile	DI0052	1.5 EPMMA	7.0397	0.2246	26.00	179	48.2	79.1	24.58	6.58	5.39
11	Tensile	DI0053	1.5 EPMMA	7.0492	0.2246	26.03	179	48.8	73.4	24.85	3.86	3.38
12	Tensile	DI0054	1.5 EPMMA	7.0451	0.2237	25.81	164	47.9	80.9	24.58	10.96	8.90
Average =				7.0418	0.2244	25.95	170	47.9	77.1	24.56	7.00	6.14
Std. Dev. =				0.0069	0.0004	0.10	11	0.9	3.5	0.26	2.94	2.34
5	Tensile	DI0056	Keel	7.0415	0.2246	26.00	163	48.6	73.9	24.96	17.05	16.70
6	Tensile	DI0057	Keel	7.0144	0.2237	25.70	163	49.7	73.5	24.77	15.95	15.32
7	Tensile	DI0058	Keel	7.0375	0.2236	25.76	156	48.9	76.6	25.12	15.58	16.88
8	Tensile	DI0059	Keel	7.0462	0.2228	25.61	163	46.9	69.9	24.39	13.90	13.05
Average =				7.0349	0.2237	25.77	161	48.5	73.5	24.81	15.62	15.49
Std. Dev. =				0.0141	0.0007	0.17	4	1.2	2.8	0.31	1.31	1.77

The EPS specimens had an average elongation of 4.29%, and PMMA specimens an average elongation of 7% compared to 15.62% for the keel block legs. The area reduction was 5.05% in EPS, 6.14% in PMMA and 15.49% keel block molds.

All of the EPC cast ductile iron property data, with the exception of strain-to-failure and area reduction, were similar to the keel block data. The total elongation and area reduction values were higher in the EPMMA cast specimens compared to the 1.4 pcf EPS. Microshrinkage and trapped debris may have played a role in reducing the elongation and area reduction values. The EPS and PMMA bars were not risered and could have some microshrinkage whereas the keel block bars were highly risered. Residual polymer debris in the unrised bars would account for the fact that the EPMMA bars had higher ductility values, compared to the 1.4 pcf EPS, since EPMMA leaves less carbon residue compared to 1.4 pcf EPS.

6.2 100-70-03 Ductile Iron Tensile and Fatigue Properties

Three sets of test specimens of 100-70-03 ductile iron were cast in a commercial EPC foundry. The first set of castings was produced in no-bake molds and cast sufficiently close to the desired size that specimens could be tensile and fatigue tested with an as-cast surface. The second set was produced by the EPC method with an as-cast surface. The third set of bars was cast as 1.2 inch diameter bars on 1.3 pcf EPS patterns and machined to the desired test bar dimensions. The chemical composition of the ASTM A536 Grade 100-70-03 ductile iron was as follows: 3.62% carbon, 0.47% manganese, 2.33% silicon, 0.009% sulfur, 0.006% nickel, 0.03% chromium, 0.713% copper, 0.001% vanadium, and 0.045% magnesium. A single heat was used to produce all three sets of specimens. All of the molds were inoculated with 75% ferrosilicon during filling, and the metal pouring temperature was approximately 2550°F.

6.3 Fatigue Specimen Preparation

6.3.1 As-cast No-bake Specimens. Test bars to produce these specimens were cast in a PepSet bonded silica sand molds. Test bar casting dimensions are shown on Figure 42. The longer end of the test bar formed a flow-off which allowed metal to pass through and heat the gauge section.

The grip ends of the specimens were machined prior to testing. Machine centers were put into each end of the test specimen to turn the grip ends of the specimens. During this operation, the machinist attempted to minimize runout at the center of each specimen. However, since the bars were as-cast, the runout on each specimen was greater than that typically found in fully machined specimens. The TIR averaged 0.010 inches (0.25 mm) for the no-bake mold cast bars.

6.3.2 As-cast EP Specimens. This group of test bars was cast on a single runner using 1.3 pcf EPS molded patterns. The foam test patterns were glued to a runner and then coated. Sand was compacted around the cluster at 2.0 G's with a low sand fill rate. The TIR averaged 0.012 inches (0.31 mm) for the EP cast tensile and fatigue specimens.

6.3.3 Machined Specimens. These specimens were cast as 1.2 inch (30mm) diameter "B" bars using 1.4 pcf EPS patterns. The foam test bars were glued

NOTE: ALL DIMENSIONS ARE IN INCHES.

Figure 42. Test Bar Pattern for As-cast EPC and No-bake Fatigue Specimens.

to a runner and then coated. Sand was compacted around the clusters at 2.0 G with slow sand fill using a GK compaction table. Maximum run out (TIR) for the machined specimens was 0.0008 inches (0.02 mm).

6.4 Test and Analysis Procedures

6.4.1 Monotonic Tensile Test Procedure. Monotonic tensile properties were obtained following recommendations of ASTM E8 for tension testing of metallic materials. Two specimens from each group were used for tensile tests. The cylindrical, reduced-section specimens were installed in a load frame using hydraulically actuated collet grips. During the tensile test, a Somat series 1100 data acquisition and control unit monitored values of load and strain measured by an Interface 1220-AF load cell and an MTS 632.26 C-30 extensometer. The test was strain controlled up to a strain of 3 percent. When a strain of 3% was achieved, the extensometer was removed and the tensile test continued under stroke control until the specimen fractured.

6.4.2 Analysis of Tensile Test Data. The tensile elastic modulus was determined by accumulating the initial data points of the tensile test in a linear regression until the r-squared value was maximized. A linear regression of the logarithms of stress and plastic strain was used to determine the strain hardening exponent which then allowed the strength coefficient to be determined. The yield strength was defined at an offset of 0.2% strain.

6.4.3 Fatigue Test Procedure. Axial fatigue tests were conducted using the ASTM E606 recommended practice for constant-amplitude, strain controlled, low-cycle fatigue testing. Each cylindrical, reduced-section specimen was installed in a load frame using hydraulically actuated collet grips. Values of stress and strain were intermittently recorded by a Somat series 1100 data acquisition and test control unit. All tests were run in completely reversed strain control (R=-1) with the cycling frequency ranging from 1 Hz at the higher strain amplitudes to 7 Hz at the lower strain amplitudes. The slower cycle rates were used at the higher strain amplitudes to prevent specimen heating and extensometer slippage. Test specimens which did not exhibit plastic strain were switched to load control after 500,000 cycles and run at 10-12 Hz. Each specimen was fatigue tested until either the specimen failed or the life achieved two million cycles, which was considered a "run-out". Failure was identified as 50% load drop.

6.4.4 Analysis of Fatigue Test Data. The total strain amplitude, elastic strain amplitude, plastic strain amplitude, tensile load amplitude, and compressive load amplitude were intermittently recorded for each specimen. Values for these parameters were tabulated at the designated stable fatigue cycle for each specimen. The "stable cycle" was defined as the cycle closest to the half-life of the specimen when data was acquired unless engineering judgement required the use of a different stable cycle.

The stress-life curve was established using a best fit linear regression ($\log N = A + B \cdot \log S$) of the data points where there were runouts. The slope of the best fit line was used to project each data point to a constant stress level to allow a frequency histogram of life versus percent failure to be determined for the chosen stress. A Weibull analysis was then made to establish a B50

and B10 life at the chosen stress. Using the B50 and B10 lives at the reference stress, and the slope from the linear regression, the B50 and B10 stress-life fatigue curves were determined.

The strain-life curve was fit to the data by summing the elastic strain-life curve and the plastic strain-life curves. The elastic strain-life curve was fit using the linear regression and Weibull analysis technique described above. The plastic strain-life curve was fit using a linear regression of data points with at least 50 microstrain of plastic strain.

6.5 Microstructural Examination

6.5.1 As-cast No-bake Specimens. A typical surface of a fatigue specimen cast in a no-bake mold is shown in Figure 43 (A). There were two distinct features on the surface of these specimens. In many areas, the surface was rough due to adhering sand, as illustrated. The gauge section of one specimen was sectioned normal to the longitudinal axis for examination. Pits near the surface are illustrated in Figure 43 (B). The graphite nodules illustrated in Figure 43 (B) were mainly ASTM A247 Type I with nodularity greater than 90%. The nodule size was 7, and nodule count was around 300 per mm². The matrix microstructure, Figure 44 (A) consisted of pearlite with less than 5% ferrite. Steadite was not observed.

A similar microstructure at the surface of a specimen is illustrated in Figure 44 (B). Small amounts of carbides were found near the surface of this specimen. The graphite remained nodular in shape to the specimen surface, and the relative amounts of pearlite and ferrite were essentially constant from the center to the surface of the specimen.

A typical fracture surface from a no-bake test specimen at a magnification of 10X is illustrated in Figure 45 (A). A notch resulting from sand at the surface is illustrated in Figure 45 (B) and a notch caused by a pit at the surface is shown in Figure 46.

6.5.2 As-cast EPC Specimens. A typical surface of a fatigue specimen produced by the EPC process is shown in Figure 47 (A). The surface bead pattern is obvious. The gauge section was sectioned normal to the longitudinal axis to prepare a metallographic specimen and a typical structure is shown in Figure 47 (B). Surface depressions resulting from the intersection of beads are evident. The EPC process itself did not appear to have caused any changes in the graphite or matrix microstructure as shown by the microstructures in Figures 47 (B) and 48 (A).

The graphite nodules illustrated in Figure 48 (A) were mainly ASTM A247 Type I, with nodularity greater than 90%. The nodule size was 6 to 7 and the nodule count was around 300 per mm². The matrix microstructure consisted of pearlite with less than 5% ferrite, as illustrated in Figure 48 (B). Steadite and free carbides were not found. The graphite remained nodular and the relative amounts of ferrite and pearlite remained essentially constant to the specimen surface.

Typical fracture faces are shown in Figures 49 (A) and 49 (B). Failures initiated at the surface of the specimens at depressions located at the

(A)

(B)

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Figure 43. (A) Rough Sand Surface on No-bake Cast Specimens. 10X
 (B) Cross Section of Rough Sand Surface on a No-bake Cast Specimen. 50X

(A)

(B)

616-206b

Figure 44. (A) Matrix Microstructure in a No-bake Cast Specimen. 100X 2% Nital Etch
 (B) Surface Microstructure in Gauge Section of a No-bake Cast Specimen. 100X 2% Nital Etch

(A)

(B)

616-206c

Figure 45. (A) Typical Fracture Face of a No-bake Cast Specimen. 10X
 (B) SEM Micrograph Showing Rough Sand Notch on a No-bake Cast Specimen. 50.7X

616-206d

Figure 46. SEM Micrograph Showing Pit on a No-bake Cast Specimen. 50.7X

(A)

(B)

616-206e

Figure 47. (A) Typical EPC Specimen Gauge Section Surface Finish. 10X
 (B) Surface Depression From Bead Intersection on EPC Specimen. 50X

616-206f

Figure 48. (A) Graphite Structure in an As-cast EPC Surface Specimen. 100X
(B) Matrix Microstructure in an As-cast EPC Surface Specimen. 100X

(A)

(B)

616-206g

Figure 49. (A) Typical Fracture Face of EPC Specimen. 10X
 (B) SEM Micrograph Showing Bead Intersection Notch on EPC Specimen. 50.3X

intersection of three beads. The notch effect of the depressions is clear in Figure 49 (B). Note that some debris (bright spots) are present on the specimen surface in Figure 49 (B). The debris was not related in any way to the specimen failures.

6.5.3 Machined Specimens. A typical microstructure of a machined fatigue specimen is illustrated in Figure 50. The graphite particles illustrated in Figure 50 (A), were mainly ASTM A247 Type I with nodularity greater than 90%. The nodule size was 6 to 7 and the nodule count was 200-250 per mm². The matrix microstructure, illustrated in Figure 50 (B), consisted of pearlite with less than 5% ferrite. Steadite and free carbides were not seen.

Typical fracture faces are illustrated in Figures 51 (A) and 51 (B). Failures initiated at the machined surface of the specimen at graphite particles and/or small areas containing microshrinkage.

In summary, the material of the three sets of fatigue specimens was quite consistent. Matrix microstructures were perlitic with only traces of ferrite adjacent to the graphite nodules. Steadite was never seen, and carbides were present only in a shallow layer at the surface of the no-bake cast specimens. Nodule counts were high in the specimen gauge sections as a result of the small cross section cast. As expected, the machined test specimens had somewhat lower nodule count and slightly larger nodule size because of a heavier as-cast section.

6.6 Tensile and Fatigue Test Results

Tensile and fatigue test results for the three series of test specimens are summarized in Table 7. The stress-life, strain-life, and stress-strain results for the three types of specimens are illustrated in Figure 52 through 54, respectively.

All of the materials conformed to ASTM A536 Grade 100-70-03 mechanical property requirements. The larger as-cast section size of the machined specimen group resulted in somewhat lower tensile strength and hardness, compared with the EPC and sand cast specimens. However, the fatigue properties of the machined specimens were superior to those of specimens with as-cast surfaces.

At short cycle lives (high strain amplitudes), the basic material properties including strength and toughness dominated fatigue properties so there was little difference between the three surface conditions. At high cycle lives (low strain amplitudes), fatigue properties become very sensitive to surface condition, soundness, inclusion shape, size and distribution, etc. Specimens with a sand cast surface showed a reduction in B50 stress amplitude of 29% at 2,000,000 cycles while specimens with as-cast EPC surface showed a reduction in B50 stress amplitude of 42% compared to machined surfaces on EP castings.

Certainly some of the degradation in fatigue properties was due to surface finish effect. The difference in runout between the three sets of specimens should not to be overlooked. Test specimen straightness and fatigue properties both decreased, going from machined to sand cast to EPC specimens.

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Figure 50. (A) Graphite Structure in a Machined Surface Specimen. 100X
 (B) Matrix Microstructure in a Machined Surface Specimen.
 100X 2% Nital Etch

(A)

(B)

616-206i

Figure 51. (A) Typical Fracture Face of a Machined Surface Specimen. 10X
 (B) SEM Micrograph Showing Typical Machined Surface Specimen
 Original. 50.7X

Table 7.

**Summary Of Tensile And Fatigue Test Results
For 100-70-03 Ductile Iron Specimens.**

Surface Condition	Ultimate Strength ksi (MPa)	0.2% Offset Yield Strength ksi (MPa)	R/A %	Hardness (BHN)	B50 Stress Amplitude		
					10 ³	10 ⁵ ksi (MPa)	2 x 10 ⁶
Machined Surface	116.44 (803)	73.95 (510)	4	247	76.56 (528)	56.12 (387)	45.97 (317)
	123.83 (854)	73.81 (509)	4	247	—	—	—
EPC Cast Surface	131.95 (910)	98.31 (678)	2	279	74.82 (516)	39.88 (275)	26.54 (183)
	129.63 (894)	98.60 (680)	2	279	—	—	—
Sand Cast Surface	125.72 (867)	90.34 (623)	6	286	74.82 (516)	48.72 (336)	32.48 (224)
	117.16 (808)	89.18 (615)	2	286	—	—	—
ASTM A536	99.91 (689)	70.04 (483)	—	—	—	—	—

STRESS VS LIFE

Local ID DGDM -- Machined surface ductile iron fatigue specimens - 247 BHN
 Local ID DGDE -- EPC as-cast surface ductile iron fatigue specimens - 279 BHN
 Local ID DGDS -- No bake as-cast surface ductile iron fatigue specimens - 286 BHN

MDR VERS=2.00 DB VERS=008.000

Data Analysis ToolKit 0.5

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Figure 52. Stress-life Curve Comparison.

STRAIN VS LIFE

Local ID DGDM -- Machined surface ductile iron fatigue specimens - 247 BHN
 Local ID DGDE -- EPC as-cast surface ductile iron fatigue specimens - 279 BHN
 Local ID DGDS -- No bake as-cast surface ductile iron fatigue specimens - 286 BHN

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 Data Analysis ToolKit 0.5

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Figure 53. Strain-life Curve Comparison.

Figure 54. Stress-strain Curve Comparison.

Lack of specimen straightness can result in higher than nominal load at the specimen surface, and thus shorter life than would be obtained if the specimen were completely straight. No attempt has been made to separate the effects, and both effects are probably operative.

It should not be inferred that EPC cast surfaces will have a lower fatigue strength compared to sand cast surfaces. Improvements in surface finish to reduce the size of the depressions at bead intersections will probably improve fatigue strength significantly, since it appeared that the reduction was due to geometrical notch effects rather than degradation of the material microstructure.

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