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CONTRACTOR REPORT ARLCD-CR-80018

SQUEEZE CASTING 81MM M374 MORTAR BODY
AND 155MM M483 PROJECTILE BODY PREFORM

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JUNE 1980



US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND
LARGE CALIBER
WEAPON SYSTEMS LABORATORY
DOVER, NEW JERSEY

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER ARLCD-CR-80018	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Squeeze Casting 81mm M374 Mortar Body and 155mm M483 Projectile Body Preform		5. TYPE OF REPORT & PERIOD COVERED Final Report, 26 September 1978 to 31 March 1980
		6. PERFORMING ORG. REPORT NUMBER IITRI - M6012-6
7. AUTHOR(s) S. Rajagopal, A. Chakravartty, IITRI Duane Gustad, Project Engineer, ARRADCOM		8. CONTRACT OR GRANT NUMBER(s) DAAK-78-C-0393
9. PERFORMING ORGANIZATION NAME AND ADDRESS IIT Research Institute 10 West 35th Street Chicago, Illinois 60616		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS MMT Project No. 5786681
11. CONTROLLING OFFICE NAME AND ADDRESS ARRADCOM, TSD STINFO (DRDAR-TSS) Dover, NJ 07801		12. REPORT DATE June 1980
		13. NUMBER OF PAGES 74
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) ARRADCOM, LCWSL, Munitions Systems Division (DRDAR-LCU-M) Dover, NJ 07801		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES This project was accomplished as part of the US Army's Manufacturing Methods and Technology Program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in production of Army materiel.		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Squeeze casting Ferrous casting Liquid metal forging Casting MMT-Casting		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The project described in this report demonstrates the feasibility of squeeze casting two specific munitions components: the 81mm M374 mortar body and a preform for the 155mm M483 projectile body. Squeeze casting is a hybrid of conventional casting and forging techniques which involves one-step conversion of molten metal into near net-shape components or preforms. Also termed "liquid metal forging," this process involves pouring molten metal into metallic dies in a hydraulic press and solidifying the metal under high		

20. (cont'd)

hydrostatic pressure through the application of direct press tonnage.

In this program, both pearlitic malleable iron and ductile iron were evaluated for squeeze casting of the mortar body. Ductile iron proved to lend itself better to squeeze casting and was selected for optimization studies. The preform for the 155mm M483 body was squeeze cast from 1340 steel.

The first phase of the program involved optimization of process parameters to produce consistently sound squeeze castings. The second phase examined the reproducibility of squeeze casting the mortar body through a "pilot production" run which employed the optimized process parameters established in phase one. Both phases have been completed successfully and are described in this final report together with cost estimates for squeeze casting the mortar body on a production basis.

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INTRODUCTION

This program was aimed at demonstrating the feasibility of squeeze casting the M374 mortar body and the M483 projectile body preform. The material for the mortar body was selected from ductile iron and pearlitic malleable iron, based on their relative squeeze casting performance and end properties obtained during the initial trials. The projectile body preform was squeeze cast from SAE 1340 alloy steel. The possible enhancement of properties resulting from squeeze casting these materials and the potential for cost reduction were two areas of major interest.

This study was organized in two phases. During Phase I, the squeeze casting dies were designed and built, and the parameters governing the process were studied and optimized. Phase II involved producing 50 deliverable squeeze castings of the mortar body, using the optimum range of process parameters, for inspection and nondestructive testing.

The technical data obtained during this program were used in conjunction with economic factors to arrive at cost estimates for large-scale manufacture of the mortar body (which has definite near-term applications in production), and to demonstrate the cost savings that can be realized through squeeze casting this component.

TECHNICAL BACKGROUND

Process Description

Although it is a relative newcomer to the Western hemisphere, squeeze casting has been investigated for a

long time in the USSR. Russian literature credits D. K. Chernov with first suggesting this process in a report of the Imperial Russian Metallurgical Society in 1878. An excellent treatise on the subject has been compiled by Plyatskii⁽¹⁾ covering the basic principles, process details, tooling design, equipment requirements, and specific applications in research and industry.

Squeeze casting (fig. 1) consists of melting the work material; metering it through a tundish, into a die cavity, moving the die in a cart into the press, bringing the punch down to displace the liquid (or partially solid) charge, applying pressure during solidification, and, finally, opening the dies to eject the casting.

The application of pressure forces liquid metal into the interdendritic spacings within the partially solidified charge, melting the dendritic skeletons and feeding molten metal from hot spots into incipient shrinkage pores. In order to accomplish this, it is important to displace metal and apply the pressure at the "zero fluidity temperature" which, for steel, lies midway between the liquidus and solidus temperatures. In this zero fluidity regime, a continuous network of solid-phase skeletons is dispersed throughout the alloy. Pressure application in this regime force-feeds liquid to eliminate porosity while gases are held in solution.

Another interesting phenomenon associated with squeeze casting is the upward shift of the equilibrium

⁽¹⁾V. M. Plyatskii, Extrusion Casting, Primary Sources, New York, 1965.

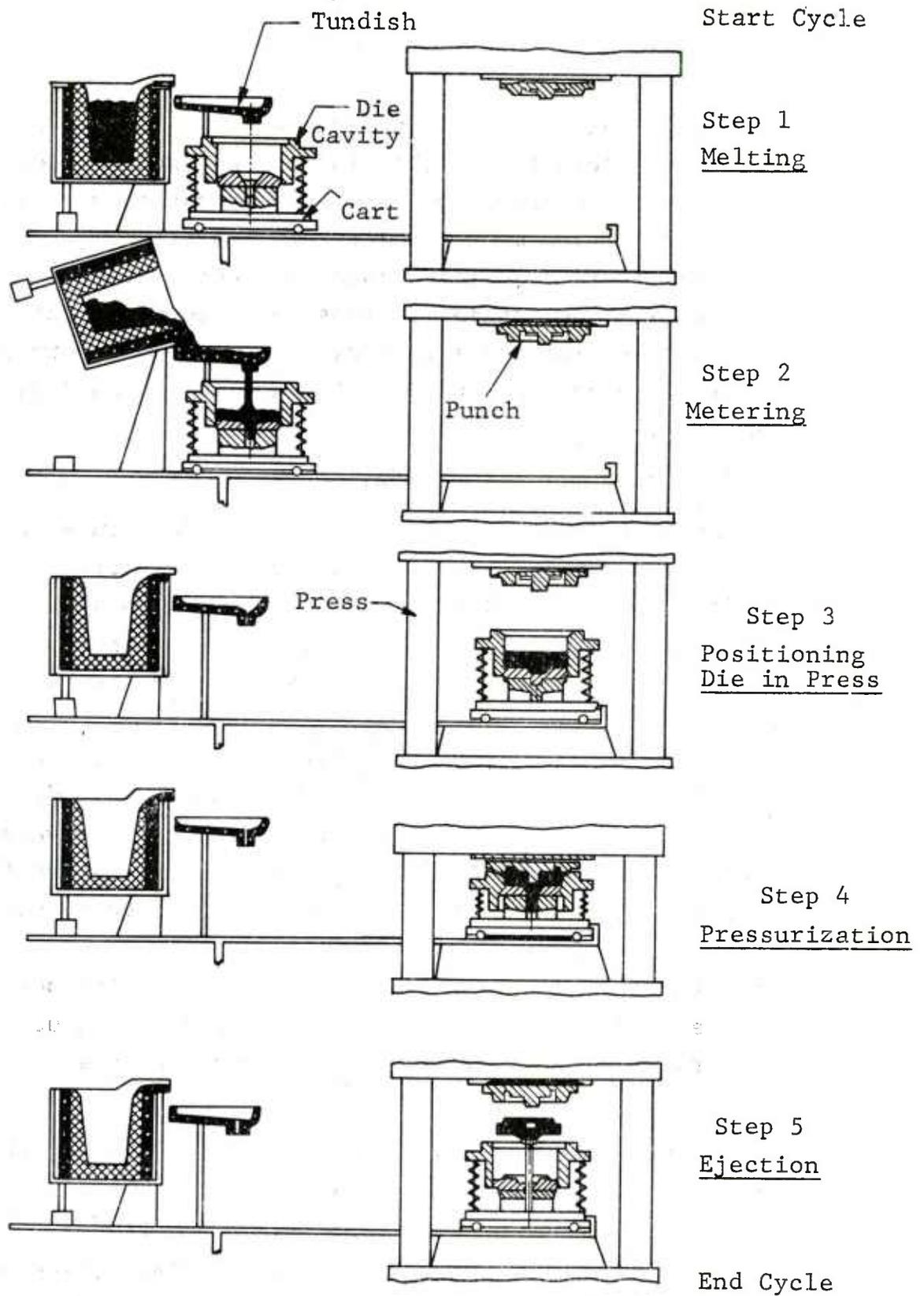


Figure 1. Production sequence for squeeze casting

diagram for alloy systems under pressure. The application of pressure raises the liquidus and solidus temperatures. Consequently, when squeeze casting pressure is applied to the metal in its zero fluidity regime, the pressure causes almost instantaneous solidification. Coupled with the intimate, pressure-induced contact with the metallic dies, this results in a finer cast structure than is possible with most conventional casting practices.

Tooling and Process Parameters

Most of IITRI's squeeze casting is done in a 1000-ton hydraulic press which has a variable-capacity hydraulic pump and a nitrogen accumulator. Press speeds from 0 to 0.25 m/s can be achieved by operating with either the hydraulic pump or the accumulator as the supply of high-pressure oil. Control of the load and ram movement is achieved manually during slow-speed operations and electrically, with switches and hydraulic pressure sensors, during high-speed work. The movement of the ram can be stopped and the ram speed changed from "fast advance" to a preselected pressing speed by electrical switches and cams. The press daylight is approximately 1.2 m with a 0.6 m stroke, and the bed measures 1.3 m by 1.1 m. For smaller castings (such as the mortar body), a 250-ton hydraulic press is also used.

A typical die assembly for squeeze casting is shown schematically in fig. 2. It consists of a base block, a die wall, and a punch, the downward movement of which applies a double-action load on the solidifying casting. The die wall is supported in place by die posts and

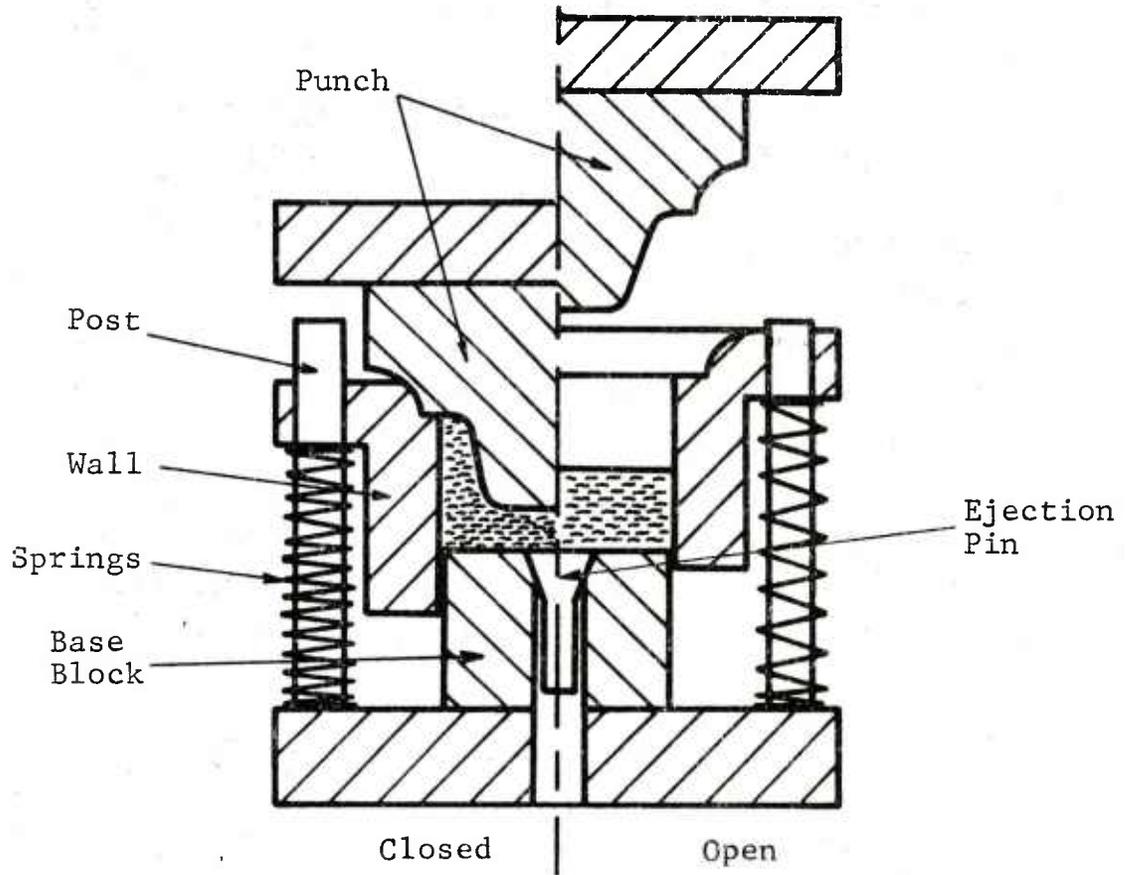


Figure 2. Cross-section of die assembly

compression springs. The ejection pin, shown in the center of the base block, ejects the casting at the end of the cycle.

For small-volume production runs typically encountered in development studies, the die material is exclusively H13 die steel. This material is moderately strong at high temperatures and resists thermal fatigue sufficiently to combat the high surface temperatures encountered in ferrous squeeze casting. For high-volume production, die life becomes of vital concern. Areas subjected to very high surface temperatures from contact with the molten steel require inserts of tungsten- or molybdenum-base materials. The H13 punch for the M374 mortar body, for example, suffered gross distortions from the high-temperature, high-pressure contact with the molten metal. Refractory materials for selected areas of the punch would considerably alleviate this problem.

In order to minimize the thermal shock, the dies are preheated to 200°-300°C and the surfaces which contact the molten metal are coated with a ceramic parting agent. In high-volume production practice, however, die heating would be obviated and cooling of certain parts of the dies and press may, in fact, be necessary (depending on the size of the squeeze cast component) to maintain a given temperature in the dies.

The work material is melted, usually under an argon blanket, in one of a series of induction furnaces ranging in capacity from 15 kg to 200 kg (equivalent of steel). The smaller furnaces are mounted onto the press itself, and melt transfer is accomplished by tilting the

contents of the furnace directly into the die cavity. In the case of larger melt volumes, a precise quantity of metal is metered into a ladle from the furnace, and the ladle is moved to the press site by means of an overhead crane. The ladle is positioned in a cart, rolled on rails into the working area of the press, and then tilted in order to effect the melt transfer.

There are several important process parameters in squeeze casting which must be controlled within an optimum range in order to produce consistently good castings.⁽²⁾ These are described below.

Casting Temperature: The temperature at which the molten steel is poured into the die cavity is extremely critical from the standpoints of both casting quality and die life. Too low a casting temperature causes inadequate fluidity in the melt during die filling, and results in incomplete die fill as well as cold laps on the casting surfaces. Too high a casting temperature, on the other hand, can cause extrusion of liquid metal through the tooling interfaces and can also result in shrinkage porosity in thick sections of the squeeze casting. The die life is also adversely affected by high pouring temperatures.

The ideal pouring temperature depends both on the liquidus temperature and on the freezing range (liquidus minus solidus) of the alloy. In general, the superheat required above the liquidus is higher for alloys

⁽²⁾ S. Rajagopal, "Squeeze Casting of Ferrous Weapon Components," Proceedings of the Tri-Service Metals Manufacturing Technology Program Status Review (Molten Metal Solidification Processes), Daytona Beach, Florida, 25-27 September 1979.

exhibiting a narrow freezing range, as these are most prone to crust formation on the die walls accompanied by poor internal quality and surface discontinuities. The casting temperature is usually selected to be 30°-150°C above the liquidus temperature, with the lower limit applicable to alloys with extended freezing range and the upper limit to narrow freezing range alloys.

Die Temperature and Pretreatment: The temperatures of the die cavity and the punch are maintained in the range of 200°-300°C. Low temperatures can lead to thermal fatigue failures in the dies and cold laps on the surfaces of the casting. Very high tooling temperatures can cause hot spots and shrinkage pores in the casting and can, in extreme cases, lead to localized melting of the die surfaces. Under production conditions, there must be sufficient bulk of material in the dies to extract heat between successive pours, augmented by selective water-cooling or steam-cooling where necessary.

Pretreatment of the die surfaces includes oxidizing the freshly machined surfaces by heating them in air to 350°C, and thereby depositing a protective coating of oxide to inhibit galling and welding. The surfaces which make contact with the molten steel must, additionally, be sprayed when hot with a ceramic parting agent. This is a commercially available mixture of alumina powder and a binder in an aqueous medium, and its integrity on the die surfaces is an important consideration in eliminating welding between the squeeze casting and the dies.

Time Delay Before Pressure Application: Since optimum results are obtained when the pressure is applied in the zero fluidity regime of the molten metal, it is sometimes necessary to wait 10-20 s prior to actuating the press for die closure and pressure application. In the case of steel castings, however, the metal reaches the optimum pressing temperature extremely rapidly owing to the high temperature differential between the dies and the molten metal. A deliberate time delay is rarely necessary, except in the case of unusually heavy-section castings which are over 60 mm in thickness.

Pressure Level: A minimum pressure level of 70 MPa (10 ksi) is required in order to eliminate shrinkage and gas porosity in steel squeeze castings. However, the last part of the casting to solidify is usually the area most susceptible to the incidence of porosity. To attain a 70 MPa pressure level in this area, the nominal pressure required--as determined by the press force divided by the plan area of the casting--may be three times this level, depending on the geometry of the squeeze casting. The M374 mortar body required up to 210 MPa (30 ksi) for complete--and consistent--elimination of porosity.

In squeeze casting, pore formation is suppressed by pressure-feeding the hot melt through a network of solid skeletons. When there is a completely solid region interrupting this flow of metal--which is what happens in the vicinity of the last region to solidify--there has to be some amount of plastic deformation of the solidified crust in order to transmit pressure

through the solid region to the still molten part of the casting.

Raising the pressure level above the minimum level consistent with sound castings has been found to provide little additional benefit, although extremely high pressures in excess of the yield stress of the casting have been reported to provide grain refinement and higher properties. This added benefit must be weighed against the increased costs resulting from a higher press capacity and the drastic reduction in die life due to the combination of high pressure and high temperature. The present state of ferrous squeeze casting technology, however, utilizes a bulk pressure (usually 70-150 MPa) which is merely adequate to eliminate all traces of shrinkage and gas porosity within the casting.

Pressure Duration: The shape and section thickness of the 'squeeze casting govern the duration of pressure necessary to ensure complete solidification under pressure. As a rule of thumb, the pressure application time is 3-5 s for each 10 mm of wall thickness, i.e., 0.3-0.5 s/mm. Beyond the minimum necessary duration, longer time delays have little benefit and can, in fact, cause wall cracking and punch retraction difficulty due to the thermal contraction of the casting onto the rigid punch. The maximum duration of pressure is about 1 s/mm.

Other Parameters: There are several secondary factors governing the success of a squeeze casting operation. The accuracy of melt pour into the die cavity heads this list. The point of melt pour is usually well protected by a ceramic pad or other refractory material, and an off-center pour into relatively unprotected areas

of the die can be disastrous in terms of melt diffusion and welding to the die. Also, during pouring, the rate of melt flow into the die should be carefully controlled. The pour should be completed rapidly enough to avoid excessive cooling in the dies, and yet not so rapidly that the resulting turbulence erodes the die wall parting agent, creating diffusion problems with the die and also inclusions within the casting. Cleanliness of the steel is always an overriding consideration, and care must be taken to avoid slag carryover and alumina inclusions which show up later as surface imperfections and sub-surface defects in the casting.

Selection Criteria for Ferrous Squeeze Castings

Successful application of the squeeze casting technology depends, to a large extent, on factors related to the choice of component. There are several factors which must be considered in this context, including the size, shape, and complexity of the component, the desirability of net shape manufacture, the economics and property levels associated with alternative production methods, and the rate of production desired.

The lower limit on the size of the part is dictated by the minimum volume of melt which can be successfully poured and pressed without premature freezing. This, in turn, depends on the shape--section thickness and complexity--of the casting; but, in general, a melt weight of less than 3 kg is extremely difficult to handle. The upper limit on the size of the casting is dictated by (a) the press load capacity, which when divided by the melt pressure requirement (usually 70-150 MPa) gives the

maximum admissible plan area; and (b) the rate of production necessary for the process to be economically attractive, since very large castings would require prolonged solidification periods.

In terms of the complexity of the casting, the potential exists for making complex shapes with good dimensional accuracy. However, this could increase the cost of tooling as well as the cycle time for processing. In general, axisymmetric shapes of near-uniform cross-section provide the greatest simplicity; and re-entrant profiles, non-circular sections, variations in section thickness, ribs and bosses, etc., introduce complexities not only in the shape of the casting but also in the tooling design and processing techniques necessary to obtain good internal quality.

Squeeze casting is extremely attractive when an improvement in properties is desired over conventional casting methods. This is made possible by solidification under high hydrostatic pressure and, in some cases, by using improved alloy compositions which are not readily castable conventionally.

Another instance in which squeeze casting would be a viable manufacturing alternative is when the cost of the raw material and/or finish machining is high enough to warrant near-net shape processing. There are several factors, as discussed earlier, which dictate the ability of a part to be made to net shape as a squeeze casting.

The rate of production is tied in with the size of the part and the selection of die materials, and is an important criterion in part selection for squeeze casting. The size of the part, in conjunction with the

maximum allowable rate of solidification, determines the cycle time to a large extent. In terms of the size of the production run, short runs of production would make it imperative to use low-cost tooling fabricated from common die steels or even mild steel. Large production runs, on the other hand, would justify the use of tungsten- or molybdenum-base inserts, sophisticated cooling systems, and so on.

The M374 mortar body and the M483 projectile body preform are both relatively simple in shape. This makes them easy to squeeze cast and, more importantly, permits the use of simple dies to make the process cost effective to implement in production. With the mortar body, variations in section thickness, from a minimum of 7.1 mm (0.28 in.) in the wall region to a maximum of 47 mm (1.85 in.) in the base region, necessitated the use of relatively high pressures for effective consolidation. This aside, both components were found ideally suited to manufacture by squeeze casting.

Advantages of Squeeze Casting

The competitiveness of ferrous squeeze casting in comparison with sand casting and forging is based on the following:

- 1) Producing complex shapes and fine details beyond the scope of casting and forging.
- 2) Improved material yield and higher production rate in comparison with casting, resulting in cost reductions whenever these considerations outweigh the extra capital investment (primarily the hydraulic press) required for squeeze casting.

- 3) Ability to use a variety of alloy compositions (wrought and cast).
- 4) Higher quality of cast product with significant improvement in as-cast properties over sand casting--in many cases obviating the need for heat treatment.
- 5) Reduced pressure requirement in comparison with forging, resulting in reductions in press tonnage and die material requirements. Together with the use of a lower-cost starting material (melt stock), these factors make squeeze casting considerably less expensive than forging.

OUTLINE OF WORK

The principal tasks of this program are listed below:

- Phase I:
 - 1) Die design and fabrication for mortar body and projectile preform
 - 2) Solidification trials
 - 3) Squeeze casting optimization for mortar body and projectile preform.
- Phase II:
 - 1) Production of 50 deliverable mortar body squeeze castings
 - 2) Testing and evaluation
 - 3) Cost analysis
- Final Report

All of the above tasks have been completed. Two sets of dies were designed and constructed in Phase I--one each for squeeze casting the mortar body and the projectile preform. A limited series of ingot casting

experiments was conducted, mainly to familiarize the operating personnel with melting and casting procedures for malleable iron, ductile iron, and SAE 1340 steel. Upon receipt of the mortar body and projectile preform dies, squeeze casting optimization trials were undertaken to establish the key process parameters (pouring temperature, die temperature, time delay between melt pour and melt pressurization, pressure level, and pressure duration) leading to sound, pore-free squeeze castings in a reproducible fashion. In Phase II, these parameters were tested in a "production" run for the M374 mortar body.

DIE DESIGN AND FABRICATION

This section describes the part geometry, target configuration as a squeeze casting, and design and fabrication of the tooling for both the mortar body and the projectile preform. A machining allowance of 2.5 mm (0.100 in.) in diameter was provided for the outside surfaces of both castings, and thermal contraction corrections were incorporated in order to result in the desired final dimensions for the squeeze casting. The major die components were fabricated in H13 steel, while less-critical support members were from hot-rolled steel.

Mortar Body

The 81mm M374 mortar body (fig. 3) is reproduced from ARRADCOM Process Drawing No. 8101. It may be described as a closed-end tube with an outside diameter of 45 mm (1-3/4 in.) at the closed end and increasing to 91 mm (3-7/8 in.) OD at the open end. The wall thickness is approximately 6 mm (1/4 in.) over the length

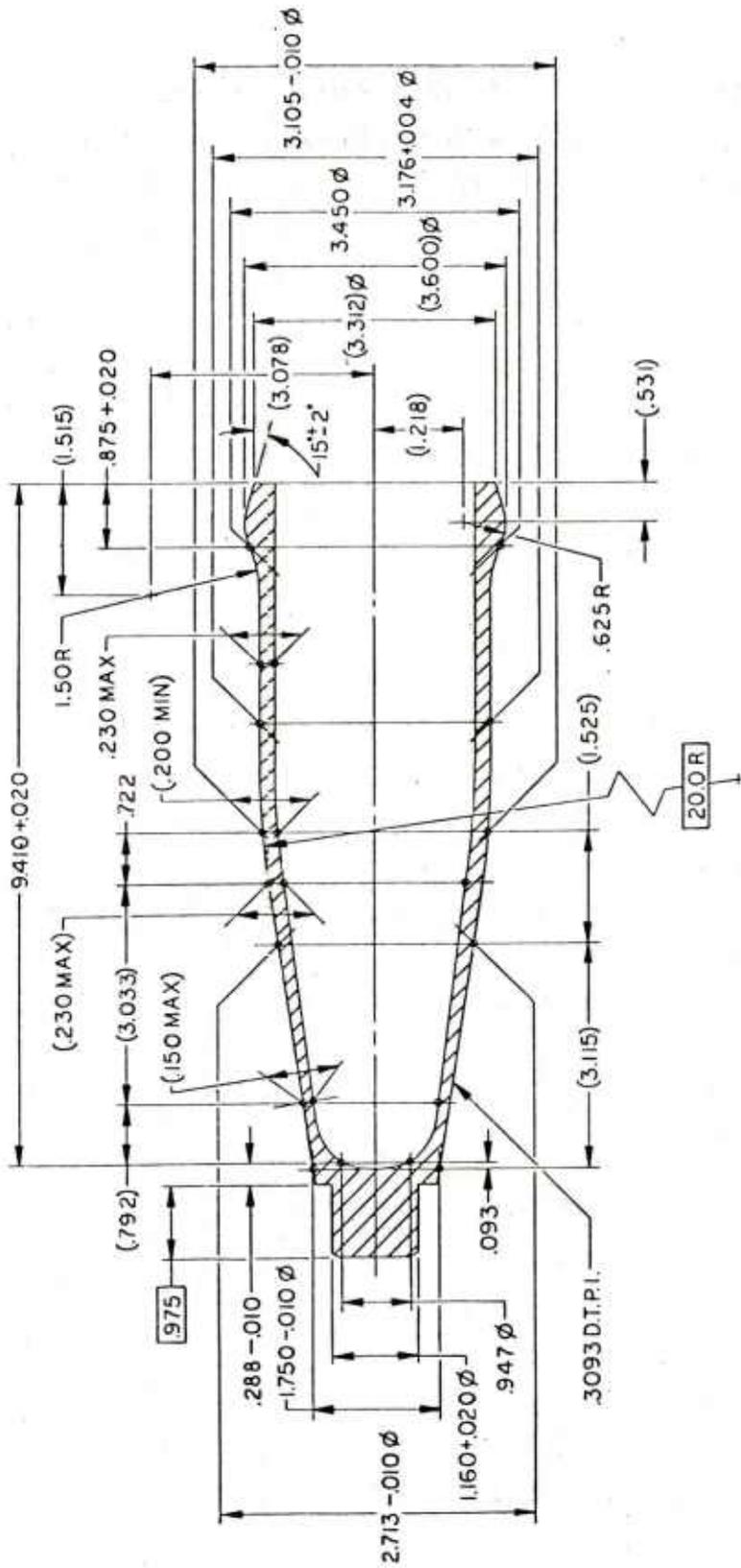


Figure 3. Mortar Body Drawing

of the body, with a thicker section (nearly $\frac{1}{2}$ in.) at the open end and a 29 mm diameter by 25 mm long (1.16 by 0.975 in.) solid projection at the closed end.

The die assembly for squeeze casting the mortar body is shown schematically in fig. 4. The outside surface of the mortar body is made by the lower die, which has a hollow cavity to contain the molten work material transferred into it at the start of the squeeze casting cycle. The inside surface of the mortar body is made by the punch. A stripper plate is used to strip the squeeze casting off the punch when the latter is retracted, leaving the casting in the lower die to be ejected by the ejection pin.

The main components of the die system, including all members that are subjected to high surface temperatures due to contact with the melt, were made from H13 chrome-molybdenum hot work die steel. This choice was based on the satisfactory performance of the material in past squeeze casting programs at IITRI. This is a commonly available, standard die steel possessing good thermal shock and medium-temperature strength properties.*

Projectile Preform

The projectile preform reproduced from ARRADCOM Drawing No. WTV-C27878 (fig. 5), is a 22 mm (8.75 in.) OD by 130 mm (5.125 in) ID by 241 mm (9.50 in.) long cylinder, with a 6 mm (0.25 in.) base thickness at one end.

*Production run experiments (in Phase II) showed the inadequacy of H13 as a punch material for this application. A refractory metal is recommended for future work, preferably augmented with forced cooling.

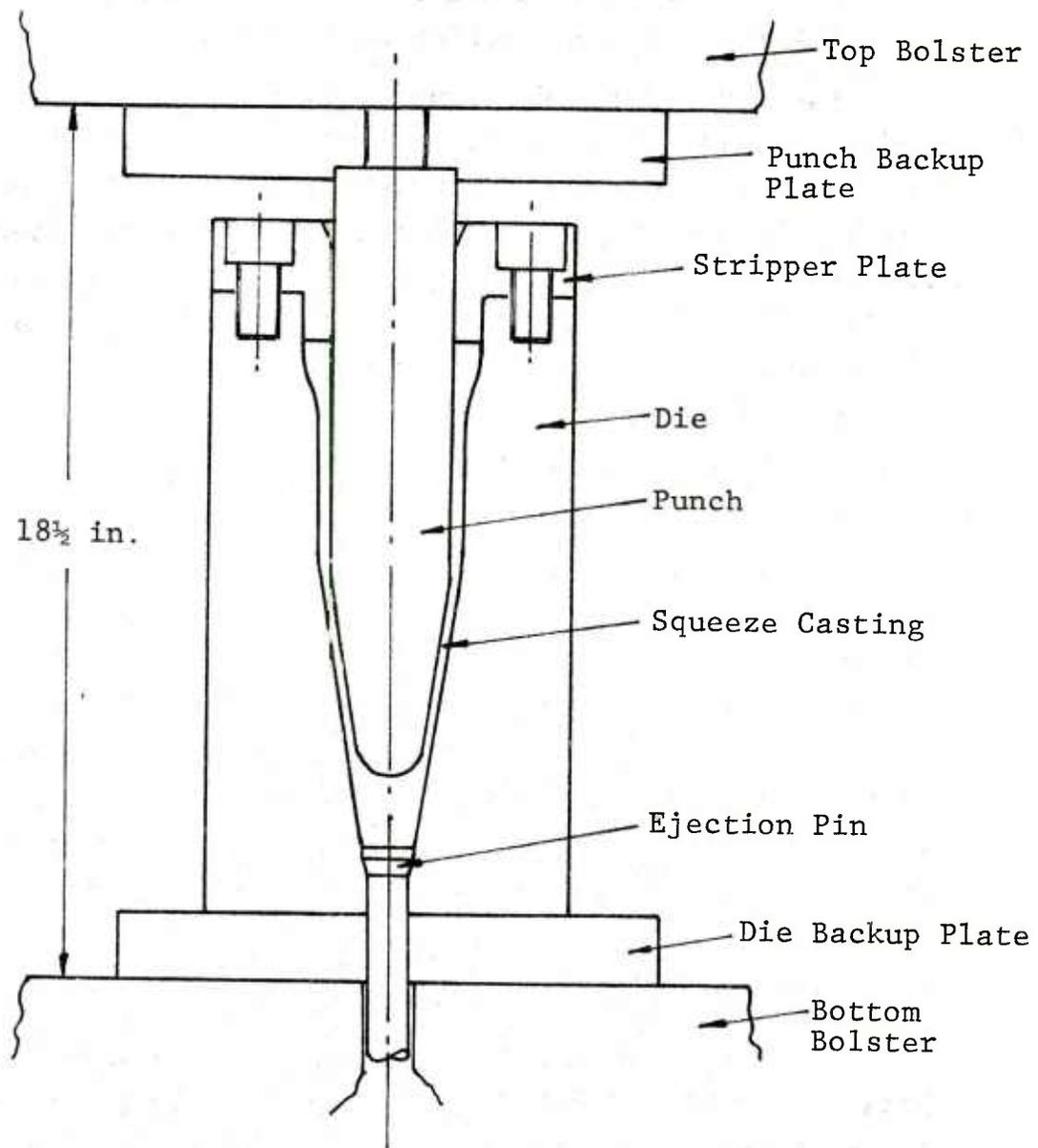


Figure 4. Mortar body squeeze casting die layout (schematic)

The die assembly for the preform is shown in fig. 6. As with the mortar body, the melt is poured into the die cavity, displaced to the final shape by the downward movement of the punch, stripped off the punch by the stripper, and ejected from the die by the ejection pin.

Dimensional Considerations

The dimensions to be specified for the die cavity are dictated by the thermal expansions of the tooling and of the squeeze casting, and by the machining allowance desired on the squeeze casting. Since the tooling expands as it reaches squeeze casting temperatures and the squeeze casting itself (mortar body or projectile preform) shrinks during cooling to room temperature, the initial room-temperature die dimensions are a function both of the thermal expansion of the die materials and of an anticipated shrinkage factor for the squeeze casting. For example, with H13 die components, the die dimensions will increase 0.0034 mm/mm at an operating temperature of 260°C (500°F) above room temperature. The magnitude of shrinkage of the squeeze casting depends on whether it is allowed to shrink unrestricted inside the die cavity or shrinks onto a rigid punch. In the first case, the casting would shrink all the way from the temperature at punch pull-out (usually about 980°C or 1800°F) down to room temperature. In the second case, shrinkage will begin to be experienced only when the temperature drops to a typical value of 540°C (1000°F), such that the yield stress of the material at that temperature exceeds the hoop stress in the casting due to contraction onto a rigid punch, thereby making the shrinkage elastic. For dimensional calculations

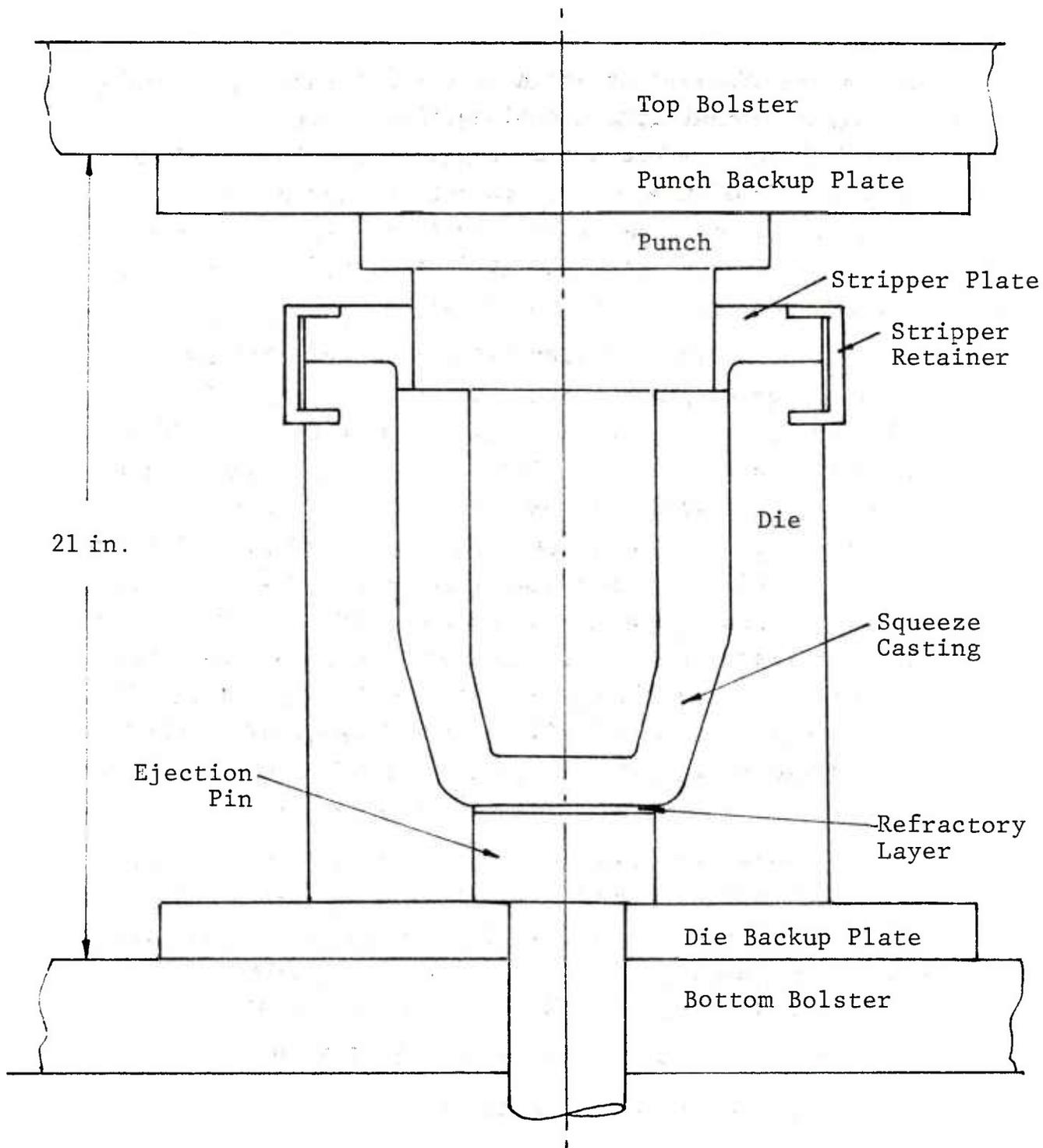


Figure 6. Preform squeeze casting die layout (schematic)

during die design, it was assumed that the squeeze casting would shrink during cooling through about 650°C (1200°F), which resulted in a casting shrinkage factor of about 0.010 mm/mm. (Dimensional measurements on the projectile preform later showed that the actual onset of shrinkage was probably at 980°C or 1800°F, resulting in somewhat smaller OD's than expected.)

The die cavity dimensions at room temperature are found by equating the casting dimensions at 650°C (1200°F) to the die cavity dimensions at 260°C (500°F) above the ambient. Thus, for a 100 mm room-temperature dimension of the squeeze casting, the casting dimension at 650°C (1200°F) above room temperature would be 101 mm, based on a 0.010 mm/mm thermal expansion. This, in turn should be the die cavity dimension at 260°C (500°F) above room temperature. The die cavity dimension at room temperature would be less than the above by 0.34 mm since the dies contract by 0.0034 mm/mm. Consequently, the room-temperature dimension of the die must be 100.34 mm to result in a squeeze casting dimension of 100.00 mm.

The machining allowances for both castings was 2.5 mm (0.100 in.) on the OD (net-shape ID). Variable machining allowances were also included on both end faces of the castings to make up for variations in the melt volume confined in the dies from pour to pour.

SQUEEZE CASTING OPTIMIZATION

Equipment and Procedural Details

Squeeze casting experiments were conducted using a 1000-ton hydraulic press for the projectile preform and a 250-ton hydraulic press for the mortar body. A 70 kg

(150 lb) high-frequency induction melting furnace was used to melt the SAE 1340 steel for the preform, while a 4½ kg (10 lb) induction furnace mounted on the 250-ton press served as the melting system for the mortar body. Standard procedures were used in both cases for melt composition control and time-temperature relationships during melting.

Mortar Body Phase I Experiments

Following an initial series of mortar body squeeze castings in aluminum, several castings were made using both nodular iron and malleable iron to evaluate their relative performance during squeeze casting. On the basis of these experiments, nodular iron, being better suited to processing by squeeze casting, was selected for further experimentation. The mortar body dies were then redesigned and rebuilt to result in a thinner casting wall closer to near-net shape. Final optimization was then undertaken.

The procedure employed for optimizing the principal process parameters (casting temperature, pressure level, delay time between pouring and die closure, etc.) was as follows:

- 1) Select melt weight required for complete die fill and correct casting dimensions.
- 2) Establish allowable range of press loads based on (a) minimum load necessary to ensure die fill, (b) maximum load beyond which metal loss (flash) is excessive, (c) maximum load capacity (design load) of tooling; and select one load high enough to eliminate porosity when all other parameters are optimum.
- 3) Select tooling temperatures for desired casting

surface quality and consistent with die life requirements.

- 4) Vary melt pouring temperature in the range of 50°-80°C (50°-150°F) superheat above liquidus.
- 5) For each of the above pouring temperatures, vary the delay time prior to die closure in the range of 0-30 s.
- 6) Cut up castings and determine optimum pouring temperature and delay time for best internal quality (no porosity) and surface finish (no cold laps, cracks, etc.).
- 7) Verify that the process is relatively insensitive to small variations in parameters about the optimum determined values.
- 8) Using the optimum value of pouring temperature and delay time, reduce the press load progressively to determine minimum necessary load consistent with casting quality.
- 9) Preliminary process specification in terms of melt weight, press load, tooling temperature, and delay time for pilot production of 50 deliverable squeeze castings (Phase II).

This procedure was followed for both the nodular and the malleable grades of cast iron (see table 1 for chemical analysis). The key experimental details are summarized in tables 2, 3, and 4.

The microstructures obtained in squeeze casting are shown in figs. 7 and 8. Figure 7 compares the as-cast microstructure of a nodular iron casting (No. N4) with the microstructure after annealing. The annealing cycle for nodular iron castings involved heating to 900°C (1650°F), holding at temperature for 1½ hr, rapid furnace-cooling to 750°C (1400°F), then slow furnace-cooling to 650°C (1200°F) at the rate of 45°C (80°F) per

Table 1. Chemical compositions of cast irons and SAE 1340 steel

Alloy	C, %		Si, %		Mn, %		S, %		P, %		Fe, %
	Actual	Aim	Actual	Aim	Actual	Aim	Actual	Aim	Actual	Aim	
Nodular Iron	3.8	3.2-4.1	2.3	1.8-2.8	0.08	0.8 max	0.008	0.03 max	0.03	0.1 max	bal.
Malleable Iron	--	2.65	--	0.9-1.65	--	0.25-1.25	--	0.05-0.08	--	0.18 max	bal.
SAE 1340	0.40	0.38-0.43	0.25	0.15-0.30	1.76	1.6-1.9	0.017	0.040 max	--	--	bal.

Table 2. Process parameters investigated during initial squeeze casting trials (nodular iron).

Casting No.	Die Temp., °F	Pour Temp., °F	Delay Time, s	Load		Porosity
				tons	ksi	
N1	450	2250	0	40	8.8	--
N2	420	2450	0	40	8.8	Yes
N3	400	2450	0	40	8.8	Yes
N4	420	2450	0	40	8.8	Yes
N5	480	2470	0	50	12.3	No
N6	540	2500	0	50	12.3	Yes
N7	460	2470	0	50	12.3	Yes
N8	500	2480	0	80	22.8	No
N9	450	2510	0	60	15.8	No
N10	550	2480	0	60	15.8	--
N11	510	2340	0	60	15.8	No
N12	380	2320	0	180	57.9	--
N13	440	2310	0	80	22.8	--
N14	470	2310	0	80	22.8	--
N15	380	2290	0	80	22.8	Yes
N16	400	2250	0	80	22.8	Yes
N17	400	2180	0	80	22.8	Yes

Note:

1. Load duration was 3-20 s.
2. Nalco alumina spray was used as parting agent, and Aquadag was used over the alumina as lubricant.
3. Beyond casting No. N7, increasing ejection difficulty was experienced. Die was relieved at the top, and the stripper plate was weld-repaired.
4. Excessive flash formation beyond casting No. N13 necessitated punch cleanup and fabrication of new stripper plate.
5. Metallographic tests indicate that the as-cast structure consists of a cementite matrix with very few graphite nodules. Subsequent annealing resulted in refined ferrite grains with a substantial increase in nodules. Nodulization was also promoted by reducing the pouring temperature and thereby reducing the rate of cooling just prior to solidification.

Table 3. Process parameters investigated during initial squeeze casting trials (malleable iron).

Casting No.	Die Temp., °F	Pour Temp., °F	Delay Time, s	Die Fill	^a	^b
					Surface Cracks	Internal Porosity
M1	420	2450	0	Good	No	Yes
M2	420	2350	0	Incomplete	--	--
M3	410	2480	0	Good	No	Yes
M4	500	2450	0	Good	Yes	Yes
M5	400	2410	0	Incomplete	--	--
M6	460	2500	5	Good	No	Yes
M7	500	2500	5	Good	No	Yes
M8	450	2500	10	Good	No	Yes
M9	440	2500	15	Good	Yes	No
M10	430	2500	25	Good	Yes	No
M11	--	2500	35	Good	Yes	No
M12	--	2510	20	Good	Yes	Yes
M13	--	2500	15	Good	Yes	Yes
M14	580	2500	15	Good	Yes	Yes
M15	480	2500	15	Good	Yes	Yes
M16	540	2600	15	Good	Yes	Yes
M17	600	2600	25	Good	Yes	No
M18	700	2600	20	Good	Yes	Yes
M19	750	2600	25	Good	Yes	No
M20	700	2600	25	Good	Yes	No

Note:

1. The press load was 100 tons (30 ksi melt pressure), and the duration of load was 3-20 s.
2. Nalco alumina spray was used as parting agent, and Aquadag was used over the alumina as lubricant.
3. Trade-off between cracks and porosity could not be resolved reproducibly.

^aCracks are formed on inside (punch side) surface of casting due to splitting of solidified crust during punch descent--more pronounced at higher delay times (heavier crust formation).

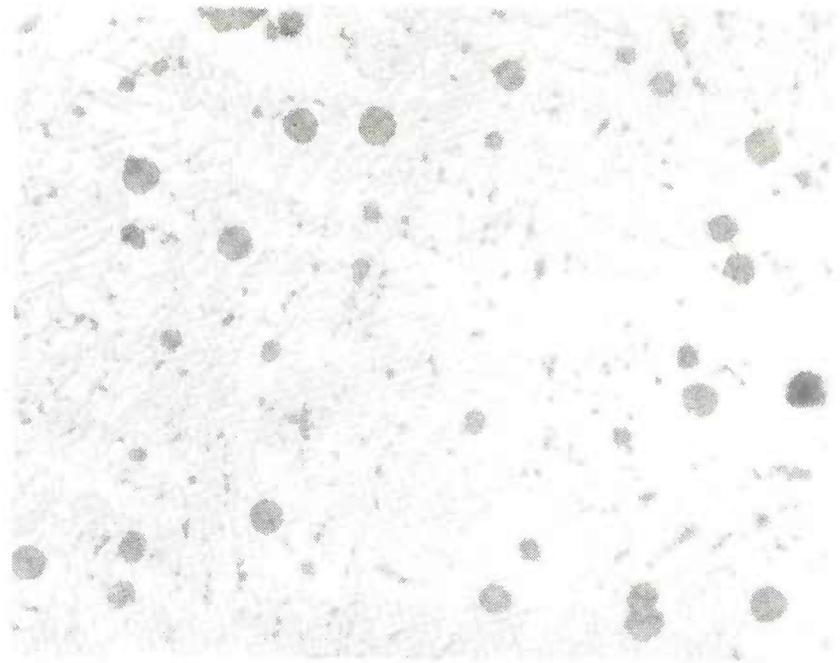
^bPorosity exists generally in the thick base region and is caused by hot spots in that region (more pronounced at high pour temperatures and short delay times).

Table 4. Process parameters investigated to optimize squeeze casting of mortar body (nodular iron).

<u>Casting No.</u>	<u>Die Temp., °F</u>	<u>Pour Temp., °F</u>	<u>Delay Time, s</u>	<u>Porosity</u>	<u>Surface Quality</u>
N18	640	2300	0	--	--
N19	650	2300	0	Yes	Good
N20	700	2300	5	No	Good
N21	720	2300	10	Yes	Good
N22	755	2300	15	Yes	Good
N23	750	2300	60	No	Poor
N24	760	2300	30	No	Poor
N25	770	2200	0	No	Good
N26	750	2200	0	No	Good
N27	780	2200	5	No	Good
N28	780	2200	10	No	Good
N29	760	2200	15	No	Good
N30	780	2200	10	Yes	Good

Note:

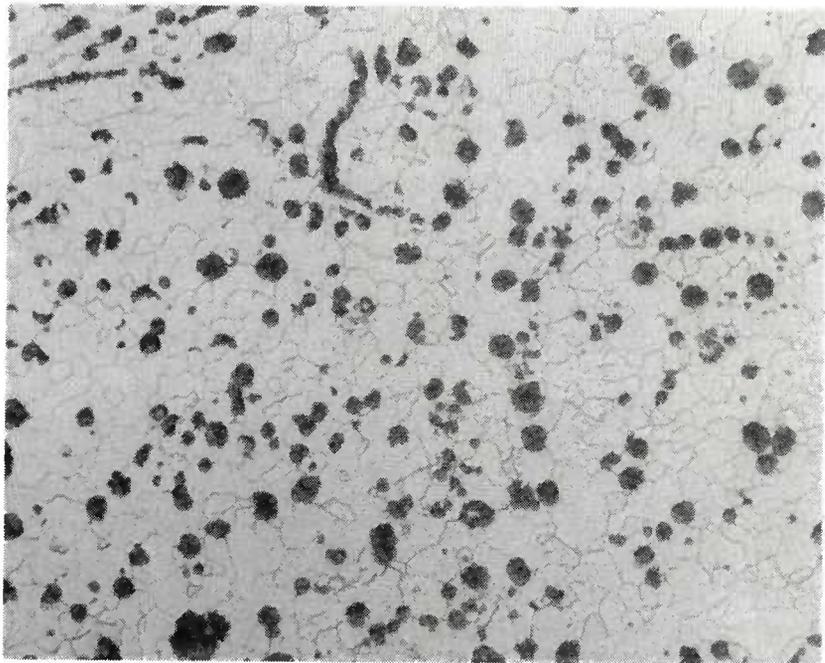
1. The press load was 100 tons (30 ksi melt pressure), and the duration of load was 2-10 s.
2. Aquadag was used both as parting agent and as lubricant.
3. Die fill was complete in all cases except No. N18 which showed evidence of excessive impurity carryover into the die.



Neg. No. 50887

200X

(a)

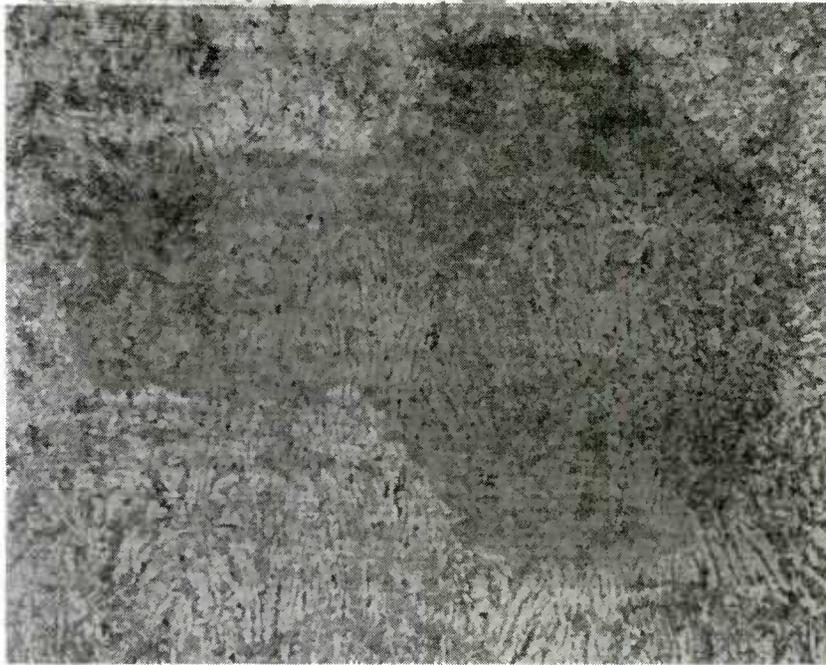


Neg. No. 50867

200X

(b)

Figure 7. Nodular iron microstructures: (a) As-cast showing massive carbide platelets, 535 BHN, and (b) annealed showing graphite nodules in a ferrite matrix, 140 BHN. Etched, 2% nital.

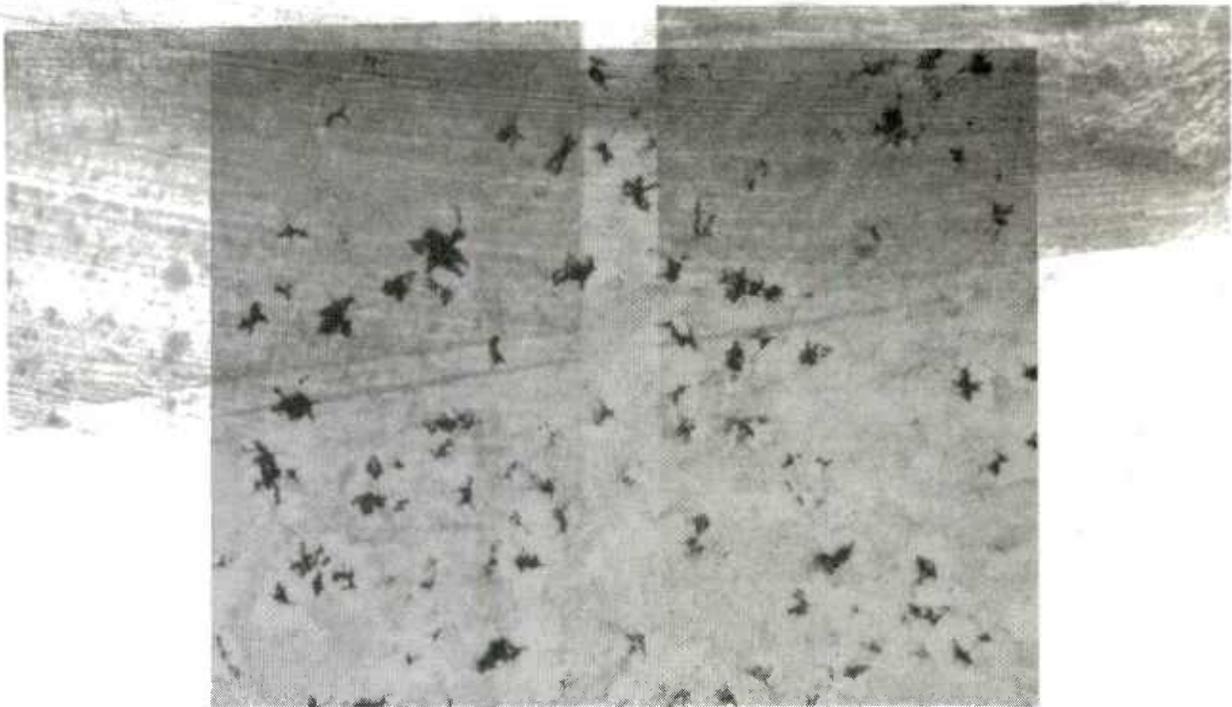


Neg. No. 51062

(a)

100X

(a)



Neg. No. 51059

(b)

100X

Figure 8. Malleable iron microstructures: (a) As-cast white iron, 520 BHN, and (b) annealed structure with extremely open nodules of temper-carbon graphite in a pearlite matrix, 145 BHN. Etched, 2% nital.

hour, holding at temperature for 4 hr, and, finally, rapid furnace-cooling to room temperature.

The as-cast microstructure of the nodular iron squeeze casting (fig. 7a) shows massive platelets of carbide formed due to the rapid rate of heat abstraction from the casting to the metallic die, with insufficient nodulization. The as-cast structure was, thus, extremely hard and brittle, the hardness being of the order of 535 BHN (3000 kg load).

The annealed microstructure (fig. 7b) shows a large number of graphite nodules in a matrix of ferrite grains, with no carbide phase present. The hardness was 140 BHN (500 kg load). The microstructure and the resulting properties may be readily controlled to within specifications by adjusting the annealing cycle after squeeze casting.

For the malleable iron squeeze castings, the as-cast microstructure of casting No. M15 is shown compared with the annealed microstructure in fig. 8. The annealing treatment in this case involved heating the casting at 1700°F for 3 hr, slow-cooling to 1600°F, holding at temperature for 2 hr, rapid-cooling to 1200°F, holding at this temperature for 6 hr, and then removing the casting from the furnace and air-cooling to room temperature.

The as-cast microstructure of the malleable iron casting (fig. 8a) consists mainly of the cementite phase typical of white cast iron. The hardness, as-cast, was 520 BHN under 3000 kg load.

In the annealed condition, the microstructure consists of extremely open nodules of temper-carbon graphite in a matrix of pearlite (fig. 8b), with a hardness of 145 BHN (500 kg load).

All of the above microstructures were obtained by etching with 2% Nital after polishing.

The optimization study for the mortar body showed that nodular iron lends itself better to squeeze casting. The principal drawbacks observed in squeeze casting malleable iron were:

- 1) Generally poorer castability in comparison with nodular iron, possibly owing to its reduced carbon content.
- 2) Higher liquidus temperature, requiring a higher pouring temperature and reduced die life.
- 3) Poorer surface quality (pockmarked) due to higher temperature reaction with die parting agents.
- 4) Longer heat treatment after squeeze casting.
- 5) Increased level of internal porosity and surface cracks. There appears to be a very fine line between cracking and porosity, and it would require stringent process control for reproducibility.

Following the mortar body die modification (to produce castings with a 2.5 mm or 0.100 OD machining allowance), a series of 22 squeeze castings was made, and sample castings were examined by sectioning--destructive testing as well as by radiography and magnetic particle inspection (NDT). Table 5 contains the processing details for this series of castings.

Table 5. Process parameters investigated during final optimization studies (nodular iron).

Casting No.	Die Temp., °F	Pour Temp., °F	Casting Weight, lb	Porosity	Surface Quality
1	450	2350	8.6	No ^a	Poor
2	480	2390	8.1	Yes ^a	Good
3	500	--	8.7	No ^b	Good
4	560	2350	7.1	No ^b	Good
5	580	2350	8.4	-- ^c	Good
6	580	2350	7.6	No ^a	Good
7	580	2350	7.2	-- ^c	Good
8	630	2200	7.8	No ^a	Good
9	560	2230	7.5	-- ^c	Good
10	650	2370	8.0	No ^b	Good
11	530	2350	8.0	No ^b	Good
12	610	2350	7.9	Yes ^{a, b}	Good
13	630	2350	7.7	No ^b	Good
14	700	2350	7.7	No ^b	Good
15	650	2350	7.9	No ^b	Good
16	650	2350	7.9	No ^b	Good
17	650	2350	7.8	No ^b	Good
18	650	2300	7.9	No ^{a, b}	Good
19	650	2350	7.6	No ^{a, b}	Good
20	650	2350	7.6	No ^b	Good
21	650	2350	8.1	No ^b	Good
22	680	2350	7.3	No ^b	Good

Note:

1. The press load was 100 tons (30 ksi melt pressure), and the duration of load was 20 s.
2. Aquadag (graphite) was used as a die parting agent instead of Nalco (alumina), resulting in excellent as-cast surfaces from castings No. 4 to 22.

^aCastings were cut up to evaluate porosity.

^bCastings were radiographed and inspected by magnetic particle testing.

^cNo evaluation done.

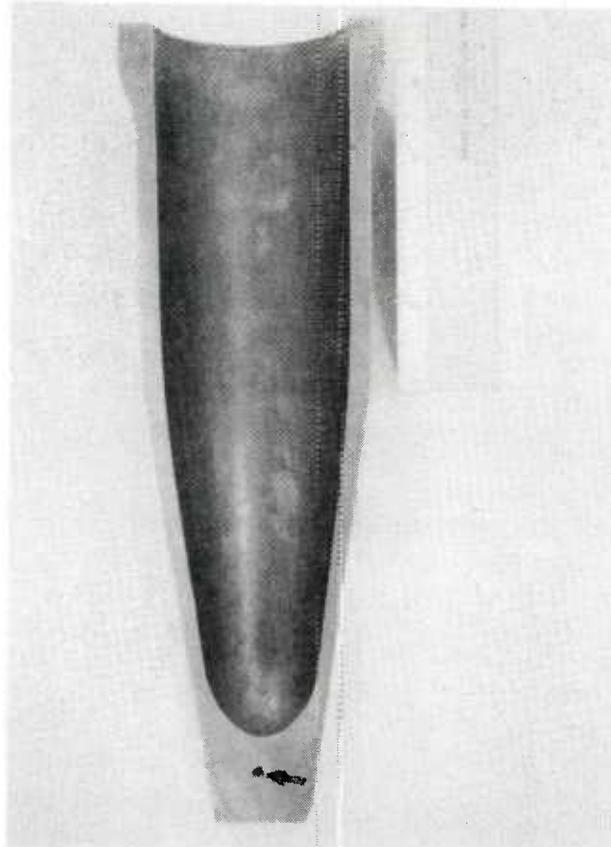
The incidence of porosity in the mortar body squeeze castings was largely restricted to the (thick) base region of the casting. While a few castings showed some porosity at the thicker part of the wall near the open end of the casting, it was the porosity in the base region that had to be controlled through the optimization of process parameters. When this was successfully done, the wall porosity was automatically eliminated.

Figure 9 illustrates a nodular iron mortar body squeeze casting with porosity in the base region. A low-magnification photomicrograph (fig. 10a) shows a shrinkage pore with no interconnected porosity. A slightly higher magnification of the same sample (fig. 10b), taken in the immediate vicinity of the pore, shows some graphite nodulization but no microporosity. The absence of microporosity in the vicinity of the shrinkage pore is again seen in fig. 10c, along with the presence of a cementite structure in which the graphite nucleation has started, but complete nodulization has yet to take place.

The sample in fig. 10 was in the as-cast condition, and the cracks indicated by the arrows in fig. 10a are grinding cracks that were developed during sample preparation. The shrinkage pore (figs. 9 and 10) is typical of the porosity encountered--and overcome--during the course of the mortar body optimization studies.

Projectile Preform Experiments

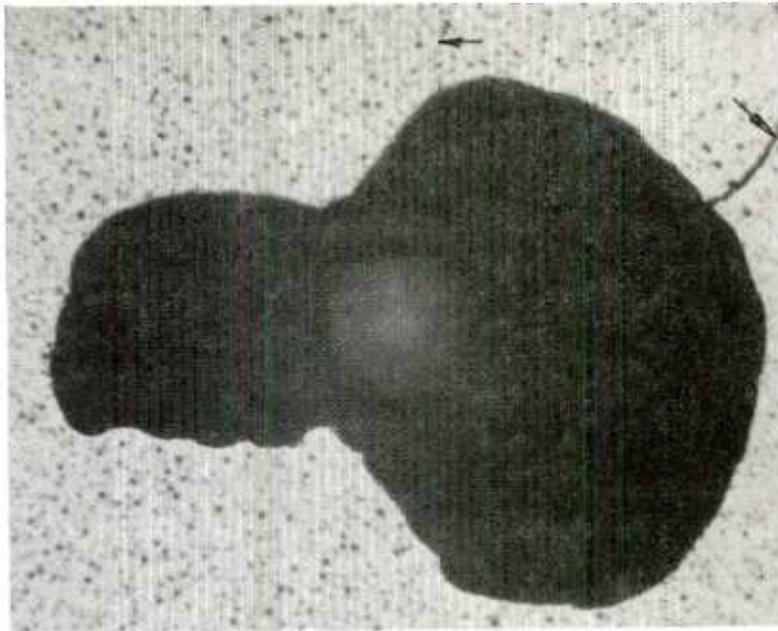
Table 6 details the experiments that were conducted to optimize the processing variables for the projectile preform. Geometry-related variables were found to be most important in influencing the product quality (porosity level)--particularly the base thickness of the



Neg. No. 51977

0.4X

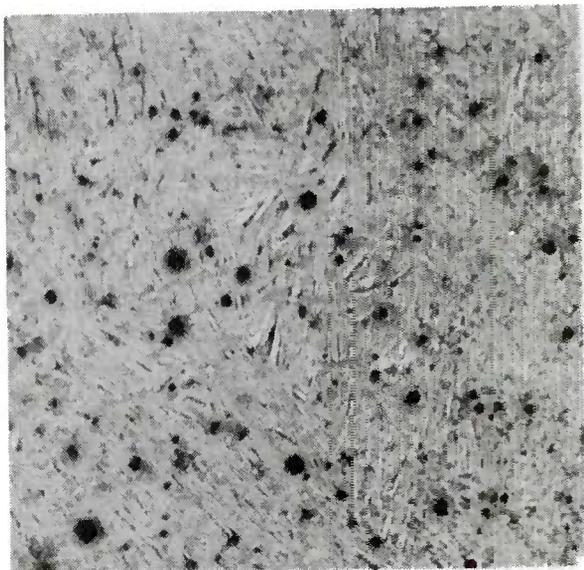
Figure 9. Cross section of mortar body squeeze casting (nodular iron) showing shrinkage pore in base region



Neg. No. 51976

15X

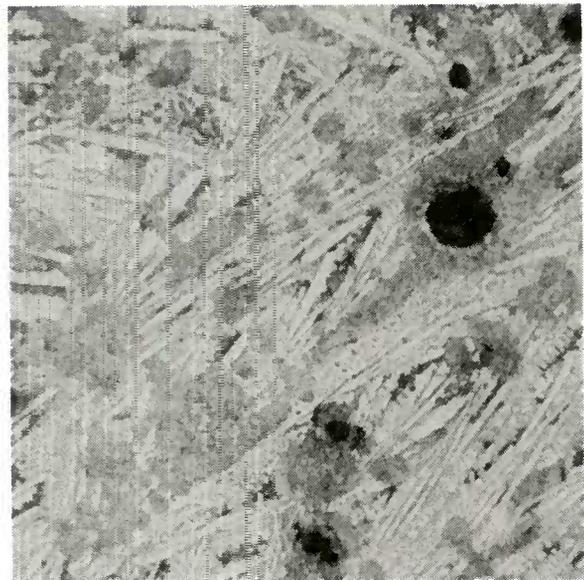
(a)



Neg. No. 51975

50X

(b)



Neg. No. 51974

200X

(c)

Figure 10. Enlarged views of shrinkage pore in base region of nodular iron mortar body squeeze casting. (a) Low magnification outline of pore, (b,c) microstructures in vicinity of pore.

Table 6. Squeeze casting data for projectile preforms.

<u>Casting No.</u>	<u>Casting Temp., °F</u>	<u>Load Duration, s</u>	<u>Casting Weight, lb</u>	<u>Die Fill</u>	<u>Surface Finish</u>	<u>Porosity</u>
1	--	10	-	Incomplete	Poor	-
2	--	60	115	Incomplete	Poor	-
3	2800	60	123	Complete	Good	Yes
4	2910	60	120	Complete	Good	Yes
5	2780	60	104	Complete	Good	Yes
6	2900	60	118	Complete	Good	No
7	2850	40	123	Complete	Good	No
8	2950	30	120	Complete	Good	Yes
9	2850	30	128	Complete	Good	-
10	2900	30	123	Complete	Good	No
11	2850	30	125	Complete	Good	No
12	2880	15	127	Complete	Good	-
13	2800	15	127	Complete	Good	No
14	2800	15	124	Complete	Good	No
15	2800	15	127	Complete	Good	-
16	2750	15	125	Complete	Good	-
17	2750	15	125	Complete	Good	No
18	2750	15	128	Complete	Good	-
19	2750	15	122	Complete	Poor	-

Note:

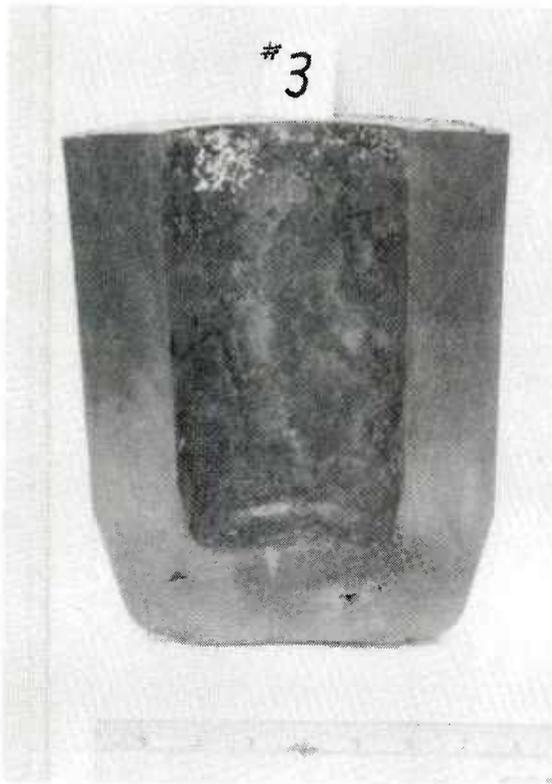
1. 400°F punch and die temperatures.
2. 400 tons press load (16 ksi)
3. Nalco alumina parting agent
4. Castings No. 1 and 2 were scrapped; castings No. 3, 4, 5, 6, 7, and 8 were sectioned for porosity evaluations; castings No. 10, 11, 13, 14, and 17 were OD machined, and inspected by radiography, magnetic particle testing and dye penetrant testing; castings No. 9, 12, 15, 16, 18, and 19 were left intact, in the as-cast condition.

casting (fig. 11). When the base is too thick (fig. 11a), hot spots developed in the base cause shrinkage pores in that region. When the base is too thin (fig. 11b), it freezes prematurely and subsequently does not transmit the punch load to the walls of the casting. The pore site is thus moved to the wall region (fig. 11b). Between these two extremes of base thickness (18 mm min. to 33 mm max.), pore-free castings can be produced (fig. 11c and 11d) with adequate latitude for errors in the poured melt weight (± 2 kg, or 4%).

Figure 12 shows the as-cast microstructure in the wall region (fig. 12a) and in the base region (fig. 12b) of a projectile preform squeeze casting. The wall of the casting was twice as thick as the base, yet the rate of heat transfer in the die during solidification was more rapid in the wall region. This is because the base begins to solidify soon after the melt is introduced into the die, with heat transfer to the die obstructed by a gas shell between the casting and the die. In the wall region, however, solidification begins only after die closure, whereupon the rate of heat abstraction is extremely rapid owing to the high pressure of contact.

The as-cast microstructure in the wall region (fig. 12a) consists of proeutectoid ferrite (light areas) at prior austenite grain boundaries and a mixture (dark areas) of ferrite and austenite grains.

In the slower-cooled base region, the as-cast microstructure (fig. 12b) consists of a Widmanstätten pattern of proeutectoid ferrite in a matrix of ferrite and pearlite. Some massive ferrite blocks in a matrix



Neg. No. 51319

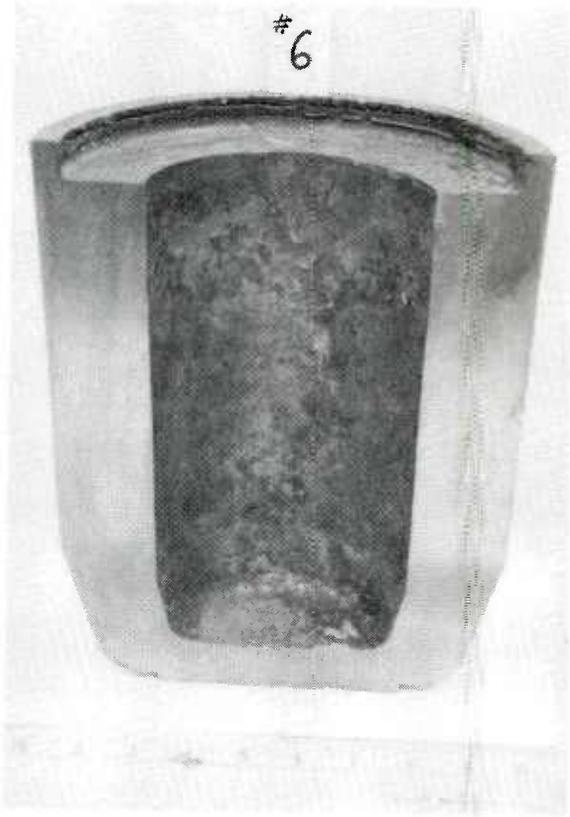
(a)



Neg. No. 51320

(b)

Figure 11. Porosity in projectile preform squeeze castings:
(a) in base region, when base is too thick; (b) in wall
region, when base is too thin; (c, d) no porosity when
base thickness is within correct range.



Neg. No. 51322

(c)



Neg. No. 51321

(d)

Figure 11 (cont.)



Neg. No. 51095

(a)

200X



Neg. No. 51097

(b)

200X

Figure 12. Microstructures of SAE 1340 preform squeeze casting in as-cast condition: (a) wall region, proeutectoid ferrite with mixture of ferrite and pearlite; (b) base region, Widmanstatten structure. 2% nital etch, 150 BHN (500 kg load).

of pearlite are also observed. The as-cast hardness of SAE 1340 squeeze castings averaged 150 BHN (500 kg load).

The casting was subsequently annealed by heating at 1600°F for 4 hr, slow-cooling to 1200°F, holding at temperature for 10 hr, and air-cooling to room temperature. The annealed microstructure (fig. 13) consists of a mixture of ferrite (light areas) and pearlite (dark areas) in which the ferrite grains seem clustered with a preferred orientation. The wall region has an almost equal distribution of ferrite and pearlite, while the base region has somewhat less pearlite owing possibly to furnace decarburization and/or a faster rate of cooling in the furnace for the thinner base region. The hardness after annealing averaged 120 BHN (500 kg load).

The wall region of the squeeze casting exhibits a uniform microstructure from top to bottom (fig. 14). The squeeze cast preform appears well suited to hot rotary forging without any need for prior heat treatment since the as-cast hardness is very low.

EVALUATION OF PHASE I SQUEEZE CASTINGS

The projectile preform and mortar body squeeze castings were thoroughly examined--both destructively (microstructures, mechanical properties, and porosity level) and by NDT (radiography and magnetic particle testing)--to verify that the optimum process parameters produce acceptable squeeze castings. The results for the projectile preform indicated that all castings produced under the optimum conditions of poured weight were radiographically sound (see table 6). Magnetic particle inspection revealed surface flaws, but these were found by dye penetrant testing to be surface depressions, not



Neg. No. 51123

(a)

200X



Neg. No. 51126

(b)

200X

Figure 13. Microstructures of SAE 1340 preform squeeze casting in annealed condition: (a) wall region, with equal amounts of pearlite (dark areas) and ferrite (light areas), the latter showing preferred orientation; (b) base region relatively depleted in pearlite. 2% nital etch, 120 BHN (500 kg load).



Neg. No. 51088

100X

(a)



Neg. No. 51090

100X

(b)

Figure 14. Microstructures of SAE 1340 preform squeeze casting, wall region, in as-cast condition: (a) Top of wall (open end), (b) middle of wall, and (c) bottom of wall (near base). Etched, 2% nital.



Neg. No. 51089

100X

(c)

Figure 14 (cont.)

cracks. Tensile test results for the projectile preform are given in table 7. In the case of the mortar body, a comprehensive evaluation of the Phase I castings was necessary in order to complete Phase II and, accordingly, the results of this evaluation are presented in detail below.

Surface Quality of Mortar Body Squeeze Castings

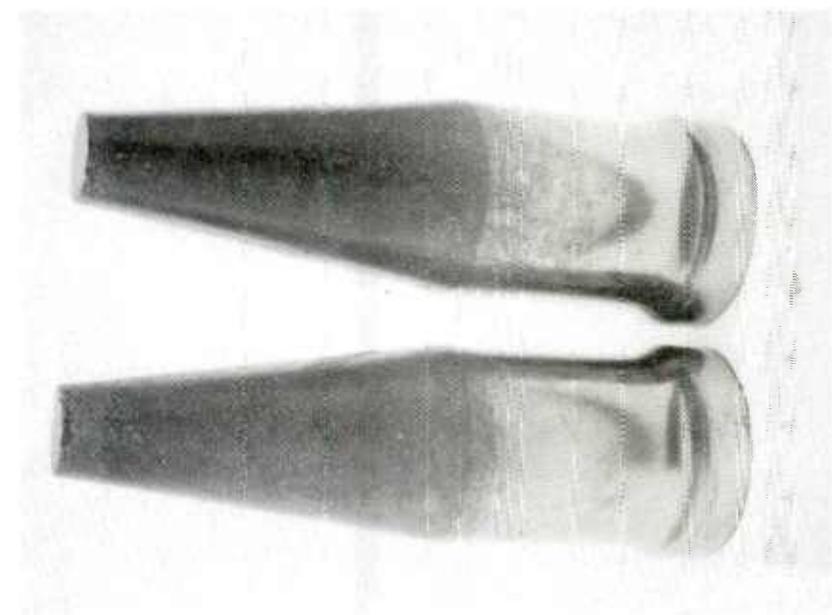
Mortar body squeeze castings (Nos. 1-22, table 5) of the final optimization study were thoroughly checked for surface quality and internal soundness. The surfaces of the castings showed two distinct characteristics. The areas corresponding to the original melt pool in the die (prior to die closure) had a uniform, but dull, and slightly pitted appearance. This can be seen in fig. 15 over the tapered length of the casting. On the other hand, the extruded areas, which saw a high contact pressure against the die, had a smooth and lustrous appearance, demonstrated by the glossy surface of the lower wall section of the mortar shell squeeze castings (fig. 15). The inside surfaces of the castings (made by the punch) were equally smooth but, overall, a light machining cut may be necessary on all squeeze castings to obtain a satisfactory finish free of local depressions and foldovers.

Wet magnetic particle testing was also performed on these castings. This revealed no cracking on the surfaces, but the shallow depressions on the casting surfaces (fig. 15) were enough to trap small amounts of the magnetic particles. In this regard, only 10% of the castings were acceptable as per MIL-I-6868. However, dye penetrant tests and visual observations showed that

Table 7. Mechanical properties of as-cast 1340 steel projectile preform squeeze casting

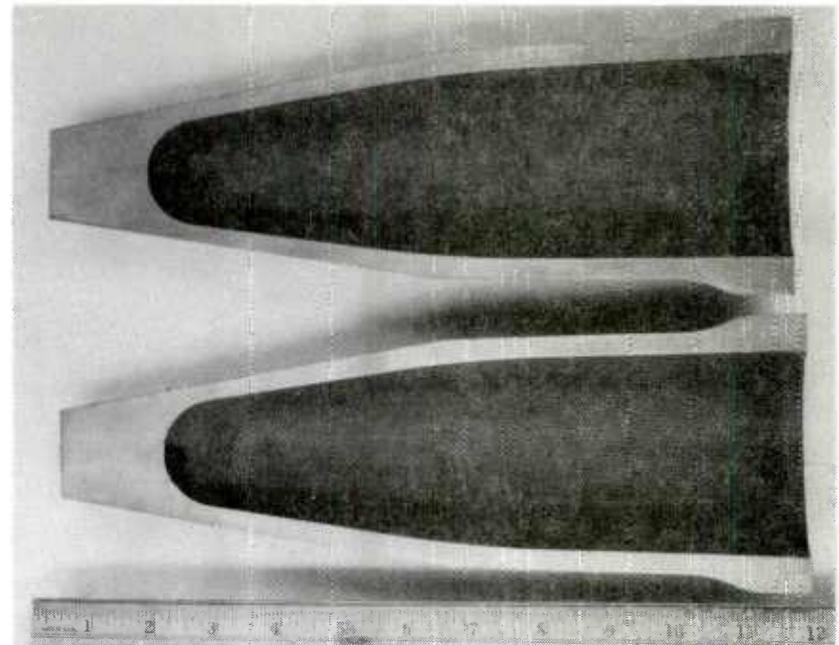
<u>Sample</u>	<u>Yield Strength, ksi</u>	<u>Tensile Strength, ksi</u>	<u>Elongation, %</u>	<u>BHN (3000 kg Load)</u>
1	52.58	82.38	3.6	207
2	54.88	102.49	13.6	207

Sample geometry: 0.350 in. dia. x 1-1/2 in. gage length.



Neg. No. 51484

Figure 15. Mortar body squeeze castings, illustrating fine as-cast surface finish



Neg. No. 51486

Figure 16. Sectioned view of mortar body squeeze castings No. 6 (right) and 8 (left), illustrating sound interior, free of porosity

magnetic particle retention was probably due to surface irregularities other than cracks. On this basis, magnetic particle inspection may not be a relevant means of testing for cracks in squeeze castings in the as-cast condition. From past IITRI experience, the mortar body squeeze castings possess a higher degree of surface finish than was hitherto possible for ferrous materials, owing primarily to the use of lower pouring temperatures for nodular iron which permitted the use of graphite, rather than alumina, as a die parting agent.

Internal Quality of Mortar Body Squeeze Castings

It was determined that the majority of the mortar body squeeze castings discussed in table 5 were completely sound internally. Sectioned halves of mortar body squeeze castings (fig. 16) revealed full densification and no porosity. Radiographic tests verified this observation: only one out of the sample population of 15 castings showed any porosity. Less dense areas observed in the radiographs were attributable to surface depressions and possibly inclusions of oxide in the wall of the squeeze castings.

Mortar Body Heat-Treatment, Microstructures, and Mechanical Properties

Heat treatment of the mortar body squeeze castings involved:

- 1) Annealing the castings in a salt bath at 930°C (1700°F) for 1 hr.
- 2) Fan-cooling the castings to near-ambient temperatures.
- 3) Tempering the annealed castings at 316°C (600°F) for 2 hr.

The above heat treatment resolved the cementite phase that predominates in the as-cast mortar body squeeze castings, and produced graphite nodules in a matrix of ferrite and pearlite. Figure 17 depicts the heat-treated microstructures at the open end or wall region of the casting (fig. 17a) and at the closed end or base region (fig. 17b). The nodular graphite (black dots) are surrounded by ferrite grains (light gray) in a matrix of ferrite and pearlite (dark gray) phases.

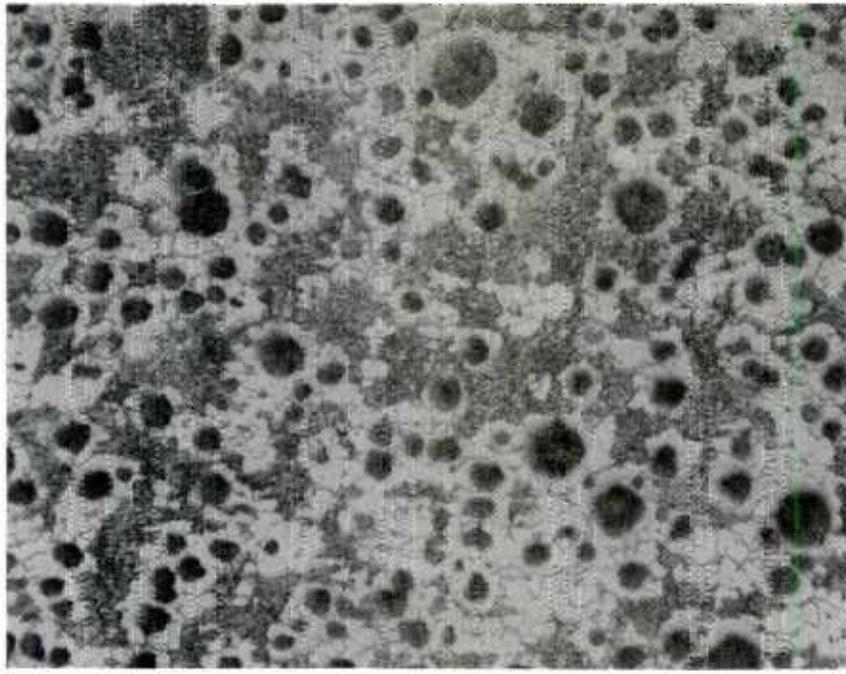
The hardness after heat treatment was in the range of 190-250 BHN. Sections of the heat-treated castings were also sent for tensile sample preparation and tensile testing. These results (table 8) indicate that minor modifications to the heat-treatment cycle may be necessary. While the strength levels were satisfactory (60 ksi in comparison with the minimum specified value of 50 ksi), the elongation values (4.7%) were marginally below the minimum specification of 5%.

PRELIMINARY PROCESS SPECIFICATION

Based on the optimization study, the following squeeze casting process parameters are recommended for production practice. (In the case of the mortar body, these parameters were subsequently employed in Phase II for the production of 50 deliverable squeeze castings.)

Mortar Body

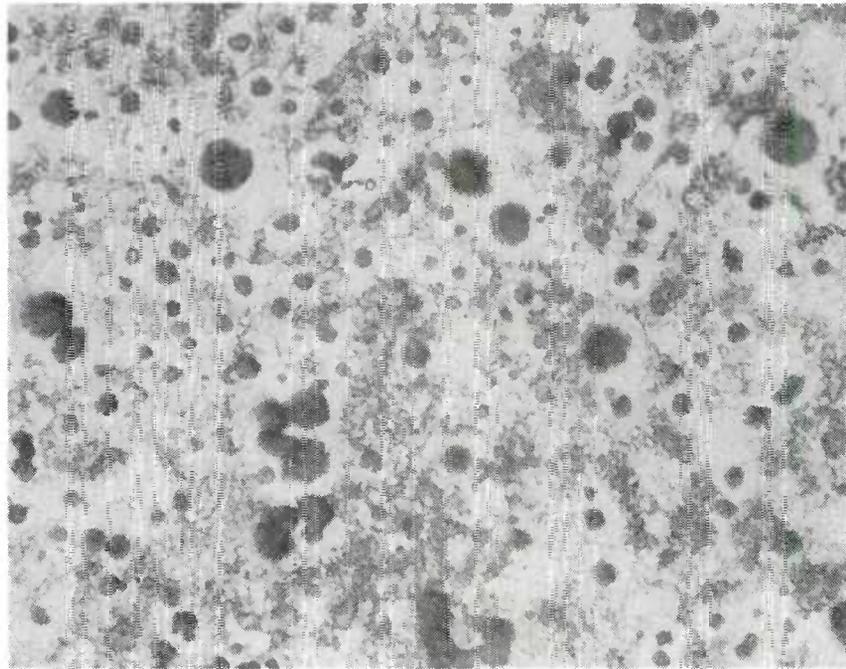
Melting Procedure: Observe standard melting procedures for ductile iron production, superheat metal to 1340°C (2450°F) and cool to desired pouring temperature. Transfer 3.21-3.30 kg (7.1-7.3 lb) of melt into die cavity for squeeze casting.



Neg. No. 51592

200X

(a)



Neg. No. 51690

(b)

200X

Figure 17. Heat-treated microstructures of nodular iron mortar body squeeze castings, showing graphite nodules in a matrix of ferrite and pearlite. (a) Casting wall region, 207 BHN. (b) Casting base region, 235 BHN. Etched. 2% nital.

Table 8. Mechanical property data for heat-treated nodular iron mortar body squeeze casting.

<u>Sample Location</u>	<u>Yield Strength, ksi</u>	<u>Tensile Strength, ksi</u>	<u>Elong., %</u>	<u>Reduction in Area, %</u>	<u>BHN (3000 kg Load)</u>
Wall--near open end	60.17	83.59	4.7	5.0	207
Wall--near closed end'	60.41	85.40	4.7	6.1	235

Sample geometry: 0.16 in. dia. x 0.64 in. gage length.

Squeeze Casting Parameters: 260°-370°C (500°-700°F) punch and die temperatures; 1260°-1290°C (2300°-2350°F) melt pouring temperature; 20 s maximum pour elapse time; 5 s maximum time delay between pouring and die closure; and 100 tons press load applied for 20 s. Oxidize freshly machined dies (prior to initial use) by heating in air to 260°C (500°F), 4 hr. Use a water-base colloidal graphite suspension (such as Acheson Aquadag hot forging lubricant), diluted in water to approximately 1:20 ratio, and apply as a sprayed coating on all surfaces of dies (and punch) exposed to molten metal.

Heat Treatment: Resolve cementite structure of as-cast squeeze castings into graphite nodules in a pearlite matrix to result in 50 ksi minimum yield strength and 5% minimum tensile elongation. A possible cycle is as follows:

- Casting preheat to 450°C (850°F)
- Casting heat-up with furnace to 930°C (1700°F) at a rate of 180°C (350°F) per hr.
- Austenitizing at 930°C (1700°F) for 1 hr.
- Furnace-cool to 790°C (1450°F) to precipitate carbon as graphite on existing graphite nodules.
- Slow cooling in air.
- Tempering at 600°C (1110°F) for 2 hr.

Projectile Preform

Melting procedure: Follow standard melting practice for SAE 1340 alloy steel, superheat metal to 1700°C (3100°F) and cool to desired pouring temperature. Transfer 54-56 kg (119-123 lb) melt into die cavity for squeeze casting.

Squeeze Casting Parameters: 177°-232°C (350°-450°F) punch and die temperatures; 1510°-1565°C (2750°-2850°F) melt pouring temperature; 30 s maximum pour elapse time; 15 s maximum delay between pouring and die closure, and 400 tons press load applied for 15 s. Oxidize freshly machined dies (prior to initial use) by heating in air to 260°C (500°F), 4 hr. Use an alumina-base parting agent (such as Nalco 839P) as a sprayed coating on punch and die surfaces.

Heat Treatment: None necessary for further processing by rotary forging, provided squeeze casting is slow-cooled in a furnace upon ejection from the die.

MORTAR BODY PRODUCTION RUN

A total of 150 mortar body squeeze castings were produced under nominally similar processing conditions. The first 22 were considered part of the optimization study (Phase I), as a means of verifying the process parameters before commencing on a larger scale experiment. These castings were described earlier in table 5.

In addition to the first 22 castings, 15 more castings (Nos. 23-37) were made under similar conditions (Phase II). However, during the course of this run, the punch was observed to lose its original shape near the tip, resulting from prolonged exposure to an environment combining high pressure (210 MPa or 30 ksi) with high temperature (in excess of 1090°C or 2000°F). The duration of pressure was 20 s.

The pressure level of 210 MPa (30 ksi) applied for 20 s was successful in eliminating porosity. It was felt that decreasing the duration of pressure to 5 s

would not affect the quality of the casting, while greatly alleviating the distortion of the punch which was becoming a matter of some concern. On this basis, a series of 59 castings was produced (Nos. 38-95), utilizing a casting temperature of 1260°-1290°C (2300°-2350°F) with solidification under a pressure of 210 MPa (30 ksi) applied for 5 s.

The reduction in pressure duration was successful in arresting the progressive deformation of the punch. However, a 100% radiographic check showed that an overwhelming majority of these castings had shrinkage porosity in the base region. The duration of pressure had to be increased to an intermediate level of 15 s to overcome this problem. The casting temperature was also raised slightly to improve the surface finish and eliminate occasional cold laps observed at the previous temperature range of 1260°-1290°C (2300°-2350°F).

A final study involving an additional 55 mortar body squeeze castings, was then made (Nos. 96-150) with a casting temperature in the range of 1320°-1350°C (2400°-2450°F), 210 MPa (30 ksi) pressure level, and 15 s pressure duration. Punch distortion could not be prevented, but base porosity was successfully eliminated.

Overcoming the problem of punch deformation in production will require the use of a punch material with better high-temperature strength than H13. An alloy of tungsten or molybdenum may be required to provide the necessary refractory characteristics. Cooling of the overheated tip of the punch may be required to maintain the operating tooling temperatures within the desired range of 260°-370°C (500°-700°F).

In accordance with contract requirements, 50 mortar body squeeze castings were then selected for heat treatment. This selection was based on surface appearance, radiographic sampling, and dimensional conformance. Table 9 summarizes the processing conditions and results for the 50 deliverable castings.

In heat treating the relatively brittle mortar body squeeze castings, the abbreviated cycle adopted by the commercial vendor (Lindberg Heat Treating Co., Chicago, Illinois) produced high thermal stresses in the castings, leading to cracks in the junction between the thin wall and the thicker base. Twenty-three squeeze castings were damaged in this manner.

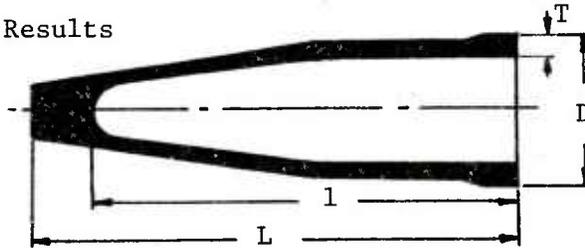
The remaining 27 castings were retrieved and heat treated by IITRI, following standard procedures. All of these castings were successfully heat treated, with tensile results conforming to target specifications. An additional ten castings were selected from the production run to replace part of the cracked quantity. The final deliverables contain 37 sound castings and 13 castings that were cracked during heat treatment, for a total of 50 deliverables.

The heat-treatment cycle employed by the commercial vendor involved:

- Casting preheat to 450°C (850°F)
- Austenitizing in a salt bath furnace at 900°-930°C (1650°-1700°F) for 1½ hr
- Rapid cooling by forced-air blast
- Tempering at 316°C (600°F) for 2 hr.

Table 9. Mortar body production run summary for 50 squeeze castings

I. Dimensional Results



<u>Dimension</u>	<u>Aim</u>	<u>Min</u>	<u>Max</u>	<u>Mean</u>	<u>Std. Dev.</u>
L, in.	11.00	10.83	11.00	10.92	0.04
l, in.	9.62	9.43	9.85	9.65	0.09
D, in.	3.70	--	--	3.69	--
T, in.	0.49	--	--	0.50 ^a	--
Weight, in.	--	6.82	7.48	7.20	0.17

^a Thickness variation was within ± 0.010 in. around periphery of any casting.

II. Casting Quality

Of the 50 deliverable squeeze castings, 11 were radiographed (No. 100, 112, 128, 139, 144, 145, 146, 147, 148, 149, and 150). This showed no porosity, but some surface depressions and inclusions appear to be present.

Some of the deliverable castings have tangential cracks in the base (near the closed end), caused by thermal stresses after ejection from the die. The cracks are shallow and within the machining envelope provided in that region. Immediate transfer from press to heat-treatment furnace is recommended to avoid these cracks in production.

III. Process Parameters

- 1320°-1350°C (2400°-2450°F) casting temperature
- 210 MPa (30 ksi) pressure level
- 15 s duration of pressure

All deliverable squeeze castings were heat treated to improve toughness and meet elongation specifications.

This cycle resulted in severe cracking (during cooling) and the following mechanical properties:

Yield strength:	61.27 ksi
Ultimate tensile strength:	73.90 ksi
Elongation:	4%
Hardness:	183-217 BHN

The heat-treatment cycle employed by IITRI--and recommended for future use--involved:

- Casting preheat to 450°C (850°F)
- Casting heat-up with furnace to 930°C (1700°F) at a rate of 180°C (350°F) per hr
- Austenitizing at 930°C (1700°F) for 1 hr
- Furnace-cool to 790°C (1450°F) to precipitate carbon as graphite on existing graphite nodules
- Slow cooling in air
- Tempering at 600°C (1110°F) for 2 hr

The above cycle eliminated cracking and attained the following mechanical properties:

Yield strength:	57.45 ksi
Ultimate tensile strength:	73.13 ksi
Elongation:	5%
Hardness:	179-207 BHN

The 50 deliverable castings are expected to be similar in properties to the sample casting that was tested, thereby meeting the target properties of 50 ksi minimum yield strength and 5% minimum elongation.

Some of the squeeze castings made in the production run are shown collectively in fig. 18.



Neg. No. 51483

Figure 18. Mortar body squeeze castings from production run.

PRODUCTION REQUIREMENTS AND COSTS

This section details the equipment and tooling needed to squeeze cast the M374 mortar body in production, the cycle times and production rates anticipated, the expected cost of a squeeze cast mortar body, energy requirements in squeeze casting, and safety considerations in squeeze casting.

Equipment and Tooling

The equipment for melting, melt transfer, squeeze casting, and parts handling should be consistent with ARRADCOM's production requirement of 200,000 M374 mortar body squeeze castings per month, or a 288 parts/hr rate of production (slightly in excess of 200,000 parts/month).

For an average casting weight of 3.25 kg (7.2 lb), and assuming that losses during melting, melt transfer, and squeeze casting add up to 10% of the metal usage, the average metal usage per squeeze casting will be 3.62 kg (8.0 lb). Since 288 squeeze castings will be produced every hour, the equipment for melting and other associated purposes must be capable of handling 1043 kg (1.15 tons) of nodular iron on an hourly basis, 8,340 kg (9.22 tons) on a per-shift basis, or 25,020 kg (27.65 tons) on a daily basis.

Squeeze casting also places special requirements on melt transfer equipment. For the nodular iron mortar body, the weight of the melt poured into the die cavity must be within ± 0.027 kg (± 0.06 lb) for the base thickness to be within ± 1 mm (± 0.04 in.). A tolerance of ± 1.57 mm ($\pm 1/16$ in.) may be adequate for the

base, in which case the poured weight of metal needs to be within ± 0.045 kg or ± 0.1 lb. Dimensional accuracy can also be achieved without the development of an accurate melt metering system for this purpose, by using a charge compensator design of the type described by Lynch.⁽³⁾

The equipment for squeeze casting the molten metal into mortar bodies would be a single-action hydraulic press of approximately 150 tons capacity, with a 1.1 m (43 in.) daylight between bolsters and 0.6 m (24 in.) stroke, 0.6 by 0.6 m (24 by 24 in.) bed area, and free descent speed up to 0.25 m/s (600 ipm), with controls for switching to a lower pressing speed before contacting the melt.

The principal equipment requirements and costs are summarized below:

- 1) Melting equipment: Cumulatively capable of melting nodular iron in quantities of 27.65 tons/day, estimated at \$100,000.
- 2) Melt transfer equipment: Needs development-- to transfer molten nodular iron into the die cavity in quantities of 3.25 ± 0.23 kg (7.2 ± 0.05 lb), unless a charge compensator can be designed into the die. No cost information is presently available.
- 3) Hydraulic press: 150 tons, single-action, 1.1 m (43 in.) daylight between bolsters, 0.6 m (24 in.) stroke, 0.6 by 0.6 m (24 by 24 in.) bed area, and up to 0.25 m/s (600 ipm) speed. The number of presses required will be discussed in subsequent sections. Press costs are estimated to be \$200,000 per unit.

⁽³⁾R. R. Lynch, "Squeeze Casting Apparatus & Method," U.S. Patent No. 4,049,040, issued 20 September 1977.

The dies for squeeze casting have to be designed to withstand internal pressures of about 210 MPa (30 ksi) at surface temperatures of nearly 1260°C (2300°F). The bulk temperatures in the punch and die would be in the range of 260°-370°C (500°-700°F), with initial preheat supplied by gas burners (or other similar means), and with temperature control within these limits achieved by circulating cooling water through channels in the punch and die. H13 steel is recommended for the die and support members, but a refractory alloy based on tungsten or molybdenum would be required for the punch to prevent bulk deformation of the tip of the punch in the high pressure-high temperature environment.

The dies may be designed as single-stage dies or as transfer dies using a carousel-type of arrangement. These systems, and their estimated costs, are discussed below.

Cycle Time and Production Rate-- Single Stage vs. Transfer Dies

The cycle time for squeeze casting an M374 mortar body is conservatively estimated to be in the vicinity of 2 min. This includes die cleaning and lubrication (30 s); melt pouring (30 s); press descent, pressurization, and retraction (30 s total); and part ejection and removal (30 s). It is quite probable that the actual time can be cut down to 1 min, but for purposes of estimating the production costs, a figure of 2 min/part will be assumed.

From the breakdown of the 2 min overall cycle time into four independent components of 30 s each, it is

apparent that a four-station transfer system can be successfully applied to obtain a fourfold improvement in the production rate per press. The transfer dies would thus produce four parts every two minutes, or 120 parts/hr/press. Assuming an 80% production efficiency factor, the actual production rate would be $120 \times 0.8 = 96$ parts/hr/press, or 70,000 parts/month/press. Three presses--each operating a four-station die--would be required to meet the monthly requirement of 200,000 parts, allowing for a 5% reject rate in the process.

Alternatively, the use of single-stage dies with an identical 2 min cycle time would require 12 presses to meet the same parts requirement.

Squeeze Casting Cost--High Productivity vs. Low Productivity Manufacture

The cost of a 1-hr production run for the mortar body squeeze casting can be expressed by the relation,

$$C = [nL (1 + k) + MN] (1 + p) \quad (1)$$

in which

C = manufacturing cost, \$/hr

n = manpower requirement

L = direct labor rate, \$/hr

k = factor for manufacturing overhead

M = raw material cost, \$/part

N = production rate, parts/hr

p = factor for G&A costs, profits, etc.

The sales price (\$) of a single casting is found by dividing the cost of an hour's run (C) by the production rate (N). Thus,

$$\$ = [n \frac{L}{N} (1 + k) + M] (1 + p) \quad (2)$$

With a cycle time of 2 min, 24 parts/hr would be produced at 80% production efficiency. A suitable multiplier of 24 is needed to get the N value consistent with 200,000 parts/month. This multiplier is 12, and is obtained in practice either with 12 presses having single-stage dies, or three presses, each equipped with four-station dies. Thus, $N = 24 \times 12 \times 12 = 288$ parts/hr. On a monthly basis, this would be marginally in excess of 200,000 parts/month.

Also, in equation 2, a wage rate for direct labor (excluding overheads) of $L = \$7.10/\text{hr}$ can be taken, based on ARRADCOM data for average contractor rates. In addition, G&A, profits, etc., usually total about 35% of the manufacturing cost, or $p = 0.35$. The cost of raw material (pig iron), at $\$0.10/\text{lb}$,⁽⁴⁾ will be $\$0.80/\text{part}$ assuming 8 lb metal usage per 7.2 lb casting. Equation 2 thus simplifies to:

$$\$ = 1.35 [0.0246 n(1 + k) + 0.80] \quad (3)$$

Let us now consider two specific cases.

Case 1: High Productivity Squeeze Casting
Using Four-Station Transfer Dies

High productivity squeeze casting will require three presses, each operating a four-station die and producing 96 parts/hr for a total of 288 parts/hr. The manpower required to maintain three press lines at these rates of production comprises: melting equipment (1),

⁽⁴⁾American Metal Market, Metalworking News Edition, 9 May 1980, p. 47.

melt transfer (3), press working (3), parts handling (3), and inspection (3), for a total of $n = 13$.

An overhead equal to 175% of direct labor, or $k = 1.75$, is appropriate for manufacture with a reasonable degree of equipment sophistication and automation.

The sales price is found from equation 3, by substituting $n = 13$ and $k = 1.75$, to be \$2.27. To this must be added the tooling depreciation cost computed below:

- i) Tooling life - 10,000 castings per cavity, 40,000 castings per four-station die, or 120,000 castings for all three press lines (17 days' production).

Punch and die cost of \$180,000 for all three press lines (\$60,000 per four-station die).

This gives a tooling add-on cost per squeeze casting of \$1.50.

- ii) Replaceable wear inserts, valued at \$600 total for all three press lines, to be replaced after each 8-hr shift or 2300 castings, for an amortization of \$0.26/casting.

The total add-on to the sales price due to tooling depreciation is thus \$1.76.

The sales price, including production costs, G&A, profits, and tooling cost is, therefore, \$4.03 per mortar body squeeze casting.

This cost is for the as-squeeze cast mortar body. It does not include heat treatment, machining, and nosing of the cast body.

Case II: Low Productivity Squeeze Casting Using Single-Stage Dies

The use of single-stage dies will necessitate 12 presses, each producing 24 parts/hr. The equipment would be manned as follows: melting equipment (1), melt transfer (12), press working (12), parts handling (3), and inspection (3), for a total of $n = 31$.

The overhead rate for this labor-intensive effort can be taken to be 150% of direct labor ($k = 1.50$). The sales price in equation 3 is thus \$3.65, excluding the amortized cost of tooling.

The added cost due to tooling amortization will be the same as before (\$1.76/part), since the cost and life of the tooling will be similar on a per-cavity basis.

The sales price in this case, including production costs, G&A, profits, and die cost would thus be \$5.41 per mortar body squeeze casting in the as-cast condition.

To summarize both of the cases considered above, the as-cast mortar body can be produced for about \$4-5.50 depending on the type of operation, for production quantities of 200,000 per month. Costs for heat treatment, machining, and nosing would be extra. The costs are based on realistic estimates of raw material cost, wages, cycle time, and tooling costs. Depreciation of plant equipment other than dies (expendable) has not been considered directly, but rather as a factor in arriving at the applicable overhead rates in each case.

Energy Requirements

Squeeze casting is an energy efficient process in terms of the energy content of the squeeze cast product.

Other processes, such as cold forging, may use less energy during the actual processing, but they make use of starting materials (wrought preforms) that already have considerable energy expended in their preparation. From the standpoint of total energy consumed, cast products usually compare favorably with wrought ones.

In comparison with conventional casting processes, such as sand casting, squeeze casting uses more energy on a per-pound basis because of the pressworking requirements. Sand casting, however, provides a metal yield of no better than 50%, resulting in considerable energy expenditure when one considers the repeated remelting of the trimmed excess of the casting. A near net-shape process like squeeze casting is thus more energy efficient in terms of the total energy content of the finished product.

The starting material for each mortar body squeeze casting consists of 3.62 kg (8.0 lb) of ductile iron, with an associated energy content of 60,000 BTU to begin with. The added energy in melting this weight of ductile iron for squeeze casting will be 7,000 BTU. To this must be added the energy consumed during the pressworking phase of squeeze casting. The total energy content of each mortar body, as-squeeze cast, is thus likely to be approximately 70,000 BTU, of which 60,000 BTU is the energy content of the starting material.

The energy consumed in the squeeze casting process itself is estimated at 10,000 BTU per mortar body casting, or 2.5 million BTU per ton, or 2 billion BTU per month for a quantity of 200,000 castings.

Again, these numbers are exclusive of heat treatment and final machining.

Safety Considerations

Safety is an important aspect of implementing any new process in production. During IITRI's 10-yr laboratory experience with squeeze casting, there have been no adverse incidents endangering either personnel safety or equipment functioning. However, there are a few potential safety hazards that bear pointing out, and these are listed below:

- 1) Excessive punch-to-die clearance can cause flashing of molten metal out of the die. Shields should be provided around the die to contain the flash, and the dies or wear inserts should be replaced when the radial clearance between the mating components (principally the punch and die) exceeds 0.5 mm (0.020 in.).
- 2) Standard procedural precautions should be observed both for melting and for pressworking.
- 3) Spillage of press oil into the working area of the press presents a fire hazard one order of magnitude greater than in hot forging, owing to the presence of molten metal. Shields should be erected to eliminate this hazard.
- 4) Dies and other working members of the tooling should be proportioned to withstand the hydraulic pressure generated within the die when the melt is pressurized. Adequate margins of safety are to be provided to prevent catastrophic die failure. In general, a wall thickness equal to 25% of the inside diameter is adequate for squeeze casting using H13 as die material.

Aside from the items listed above, the wedding of casting and forging procedures presents no unmanageable safety problems.

CONCLUSIONS

This report details the work performed by IITRI on "Squeeze Casting 81mm M374 Mortar Body and 155mm M483 Projectile Body Preform."

The work completed in Phase I includes:

- Die design and fabrication for squeeze casting the mortar body and the projectile preform.
- Solidification trials for nodular iron, malleable iron, and SAE 1340 alloy steel.
- Comparison of nodular iron and malleable iron in squeeze casting the mortar body; selection of nodular iron for further experimentation.
- Process parameter optimization for the nodular iron mortar body and the 1340 steel projectile preform.
- Detailed evaluation of both types of squeeze castings for surface quality, internal quality, microstructures, and mechanical properties.
- Production run of 22 mortar body squeeze castings.
- Preliminary process specification for squeeze casting the mortar body and the projectile preform.

The work completed in Phase II includes:

- Production run of 128 castings to verify mortar body process specification.
- Evaluation of production run squeeze castings, and selection of 50 deliverable castings.
- Cost analysis for manufacture.
- Final report.

During the course of this program, an extensive experimental evaluation was conducted to examine the feasibility of squeeze casting the M374 mortar body. Although the squeeze casting trials were made essentially under laboratory conditions and with relatively long cycle times, it can be nonetheless concluded that the process would require but a few modifications to be successful in production.

In the case of the M483 projectile body preform, only a limited number of experiments was possible. The squeeze casting process can be readily controlled to produce sound preforms, but there was not enough information generated in this program to predict the tooling performance and die life under high-volume production conditions.

For the mortar body, which was successfully demonstrated to be suitable for production by squeeze casting, a cost analysis was made for production quantities of 200,000 units per month. The results of this analysis are included in this final report, along with other aspects of production such as equipment requirements, energy consumption and safety considerations, and specific recommendations for transferring this technology to industry.

In conclusion, this program has successfully demonstrated the feasibility of squeeze casting the two target ordnance components, and particularly the 81mm M374 mortar body. The tooling requirements and the optimum squeeze casting process parameters such as die temperature, casting temperature, pressure level, and pressure duration are specified in this report.

Implementation of squeeze casting as a production process in munitions manufacture--and for the M374 mortar body as the initial product--is strongly recommended since squeeze casting offers significant advantages in terms of near-net shape manufacture, improved fragmentation potential, reduced energy consumption in manufacture, and the potential for cost reduction once it is fully implemented in production.

RECOMMENDATIONS FOR PRODUCTION IMPLEMENTATION

On the basis of this Manufacturing Technology effort, it can be concluded that the 81mm M374 mortar body is ideally suited to manufacture by squeeze casting. The first phase of this project defined an adequately broad range of operating variables within which sound castings could be squeeze cast. This was confirmed in the second-phase work which continued the "production" run to 150 squeeze castings. It was shown that castings solidified under pressure for a duration of at least 15 s are consistently sound internally. The squeeze castings also exhibited a superior degree of surface finish.

Having established the feasibility of squeeze casting the M374 mortar body, the next logical step for ARRADCOM is to arrange for the implementation of the process in production. The study presently concluded by IITRI, in addition to showing that the mortar body can be readily squeeze cast, pinpointed two key areas that need further development before embarking on a full-scale production effort.

- 1) Melt transfer and melt metering systems capable of delivering a precise and reproducible charge of 3.21-3.30 kg

(7.1-7.3 lb) of ductile iron melt into the die cavity. Alternatively, a suitable charge compensator design incorporated into the die, whereby excess metal would be diverted into a noncritical extension of the casting for subsequent trimming.

- 2) An improved material for the punch--or at least for the tip of the punch--to prevent plastic deformation of the punch tip during pressure application. The use of tungsten- or molybdenum-base punches or punch inserts, or steam-cooling of the overheated tip of the punch to maintain the punch temperature within the recommended operating limits under continuous production conditions.

In addition to the above, IITRI has found that melt cleanliness is crucial for squeeze casting. Since there are no gates and risers, virtually all of the poured metal and any nonmetallic carryover from the furnace remains in the squeeze casting. The melt transfer system could be made to incorporate commercially available bottom-pour ladles, avoiding the transfer of low-density impurities into the die.

In IITRI's view, these are the only issues that need to be studied and resolved prior to the near-term implementation of the squeeze casting process for mortar body manufacture.

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