THE UNIVERSITY OF MICHIGAN

INDUSTRY PROGRAM OF THE COLLEGE OF ENGINEERING

PRECISION-CAST ORDNANCE COMPONENTS

R. A. Flinn
G. A. Colligan

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SUMMARY

The development and use of precision-casting methods for large ordnance components results in great potential savings in cost, critical materials, and lead time, in greater flexibility of design, and in an increased number of sources. Requirements for complex and expensive machining facilities are reduced drastically.

The results of the first phase of a five-year program illustrate how vital components such as large sprockets, crankshafts, drive gears, and suspension and spindle arms made by other more expensive methods may be replaced by accurate castings by using new processes. Standard practices for these advanced applications of precision-casting techniques have been developed, and commerical production sources have been stimulated by integrating the program with industrial research groups. At the same time much needed supporting work of a general nature dealing with improved dimensional tolerances and surface finish has been conducted at The University of Michigan.

The first phase of a projected five-year program is reviewed here, and some of the components selected for investigation are in more advanced states of development than others. Furthermore, the initiation of the more recent projects has required the knowledge gained from the earlier castings.

To summarize briefly some of the principal findings, the major components which have received attention will be discussed beginning with the most advanced developments as follows: (I) development and testing completed (drive sprocket, No. 8671597); (II) development completed; under test (front and rear followers, No. 7359510, No. 7360356; final drive gear, No. 7364141); (III) engineering and design completed, ready for production of test castings [crankshaft for AV-1790 engine, No. 8717036; crankcase (completed, no further work)]; (IV) under engineering study (suspension and spindle arm, No. DTA 15910-15; outer race ring, No. 7384006; cupola, No. C8671475).

I. DEVELOPMENT AND TESTING COMPLETED

Drive Sprocket, No. 8671597.--The drive sprocket is a vital part in every tank or track-propelled vehicle. In this section, the production of cast sprockets poured in graphite permanent molds is described. These components are used without any machining of the teeth or of the bolt holes. The 28-in. diameter is maintained to ± 0.1%. A substantial reduction in cost would be realized by the use of drive sprockets, cast in graphite permanent molds. A 62% reduction in scrap material, far less lead time, great flexibility in chemistry, and improved service life are obtained with the cast sprocket compared with the fabricated type.

II. DEVELOPMENT COMPLETED; UNDER TEST

A. Front and Rear Followers Nos. 7360356 and 7359510.--At present the follower rings are made in an 83% copper, aluminum bronze. A shell-molding technique has been developed for producing these in the very low strategic index material, ductile iron. While preliminary tests indicated some scoring, new castings with superior properties with proper break-in surface coatings are expected to yield satisfactory results. At the time this project was initiated, this was the heaviest shell-molded casting in production.

B. Final Drive Gear, No. 7364141.--Following the satisfactory production of sprockets, it was natural to attempt other large components with accurately cast teeth. Accordingly, final drive gears have been produced in permanent molds which require fewer machining operations than the fabricated type. Tests of carburized and induction-hardened types have been initiated by Ordnance Tank-Automotive Command in the near future.

III. ENGINEERING AND DESIGN COMPLETED, READY FOR PRODUCTION OF TEST CASTINGS

A. Crankshaft for AV-1790 Tank Engine, No. 8717036.--The production of precision-cast steel crankshafts offers very great potential savings in machining costs and critical materials. Although the present fabricated shaft requires extensive machining, its design is still severly limited. Experimental stress analyses and preliminary castings indicate a potential saving in cost and substantial reduction of regions of stress concentration by using the cast design. Production of this part by combined permanent mold and ceramic core techniques is strongly recommended for future work.

B. Crankcase for AV-1790 Tank Engine.--Improvement of the performance of tank engines has led to the use of very heavy (4-in.-thick) sections of aluminum alloys in the crankcase. Because of the susceptibility of these heavy castings to porosity and shrinkage, only very low design stresses (3500 psi) can be used. A lighter, stronger crankcase using ductile iron or steel has been designed. Since no new application of precision processes was found necessary, this project is considered complete and ready for adoption by the manufacturing agency.

IV. UNDER ENGINEERING STUDY

A. Suspension and Spindle Arm, No. DTA 15910-15.--This is an exceedingly complex and expensive fabrication. It is anticipated that it can be produced much more economically, while increasing its strength, by further development of shell-molding techniques. Future work is recommended.

B. Outer Race Ring, No. 7384006.--If this 93-3/4-in.-diameter ring can be produced as a precision casting by extension of the technique developed for the sprocket, very substantial savings in cost and material will be obtained. Preparation and testing of pilot castings are recommended.

C. Cupola, No. C8671475.--The present production of this part as a sand casting entails difficulties with dimensions and finish. The use of precision semi-permanent mold techniques should improve the product and result in reduced overall cost.

GENERAL INTRODUCTION

Before considering the individual developments in detail, it may be helpful to review the background of this project.

The Ordnance Tank-Automotive Command of the Department of the Army, realizing the rapid improvements taking place in castings, placed this contract to investigate the use of precision-casting methods for ordnance components. This work has been conducted at The University of Michigan to avoid overemphasis of any particular method. At the same time industrial sources have been developed for all the principal parts concerned so that, at the successful conclusion of a division of the work, production facilities would be immediately available to make the part under study. Only in one case (the follower castings) has it been necessary to do the work at The University of Michigan; commercial companies were unwilling to attempt this casting because of its large size. Even in this case the development has been conducted using a commercial shell-molding machine so that, upon completion, the pattern equipment could be transferred immediately to production.

The selection of parts for development and the engineering studies have been conducted for the most part at The University of Michigan with the cooperation of personnel of the Ordnance Tank-Automotive Command. Several thousand parts received preliminary investigation before the final selection of parts was actually made. The careful detailed engineering work of the sprocket and final drive gear by personnel of the Griffin Wheel Company, and of the crankshaft by personnel of the Continental Aviation and Engineering Company, is gratefully acknowledged.

As the investigation has progressed to include components of greater weight and complexity, certain supporting work has been necessary, such as the investigation of the deflections of shell molds during and after pouring and the reduction of harmful surface reactions between the liquid metal and the mold. Most of this work has been done with little cost to the Department of the Army as doctoral research work; it is available as background material when difficult casting problems arise.

The specific parts of the investigation may now be considered in the same order as outlined in the Summary, from the completed investigations to those in the intermediate stages. For clarity and ease of comparison the same order of discussion will be used for each project insofar as data are available:

(1) Purpose of the study (i.e., why was the casting selected for study);
(2) The progress developed;
(3) Properties of castings made by the new method (dimensions, stress analysis, etc.);
(4) Service performance; and
(5) Advantages of the new method.

I. DEVELOPMENT AND TESTING COMPLETED

Cast Drive Sprocket, Part No. 8671597

1. PURPOSE OF THE STUDY

A review of the fabrication methods and the service performance of fabricated sprockets indicated great potential savings if a method could be developed for casting this part to avoid machining of the teeth and counter-bored bolt holes. The authors had had experience with semi-permanent graphite molds for railroad car wheels, and the Griffin Wheel Company was accordingly asked to consider producing sprockets in graphite molds.

2. THE PROCESS DEVELOPED

Mold Design

To emphasize the reliability of the new process, a related method, in successful commercial production for railroad car wheels, is illustrated in Fig. 1. In this technique a semi-permanent graphite mold is clamped above a pouring tube which dips into a covered ladle of liquid steel. Air pressure is applied at a controlled rate to the ladle and the metal is forced up the pouring tube and into the graphite mold at a smooth, predetermined rate. The resulting castings are free from slag and mechanical defects which are caused by irregular metal flow. Hundreds of thousands of these wheels are in highly stressed service with as-cast treads of this type.

Several interesting developments were necessary to obtain a satisfactory mold for sprockets by application of this method. To form the sprocket teeth, mold inserts were machined. Originally these were made from segments of graphite but finally a one-piece gray-iron insert was found to be completely satisfactory. In this way simple and economical maintenance of the critical tooth surfaces was possible. The details of the mold design are indicated in Fig. 2. The bolt holes were produced using zircon-sand shell cores bonded with 4% liquid phenolic resin.

The gating system is superior to that necessary for the car wheel. In place of the consumable stopper rod, used to prevent the liquid metal from running back into the ladle when the pressure is released, a restraining dam is employed. In the case of the sprocket, the metal rises in the center and flows over the dam. The pouring rate is 13 lb/sec. When the casting is filled, the pressure is released and only the excess metal drains back into the ladle.

As a result of these techniques, excellent mold life was obtained. No replacement of any parts was required and the mold was in excellent condition after pouring fifty castings. The final appearance of the gray-iron insert is illustrated in Fig. 3.

Melting Analysis Control

Melting was conducted in a 1000-lb high-frequency induction furnace for all the sprockets supplied for test. To show the general applicability to production, however, metal from a 20-ton arc furnace was used with equal success. In addition to the AISI 4150 analysis, sprockets were also poured successfully in plain carbon steel (0.70% C) and in cast armor analysis. This demonstrates rather wide flexibility in analysis. The surface obtained in cast armor is shown in Fig. 4.

The analyses of the castings which were submitted for test are given in Table I and are all within the specification for AISI 4150 indicated for this part.

3. PROPERTIES OF CASTINGS MADE BY THE NEW METHOD

Dimensional Variations of Castings: X-Ray Inspection

Measurements made of three critical dimensions (the width of the base of each tooth, the radius to tooth root, and the radius to tooth tip) are listed in Tables II, III, and IV, respectively, for all castings shipped.

To obtain a measure of the variation of these dimensions caused by the casting process, and to eliminate those which could be corrected by remachining of the gray-iron tooth chiller, the data of Figs. 5, 6, and 7 were developed. These graphs indicate that the variations of a given tooth, within 95% confidence limits, are as follows:

Tooth-base width:	± 0.005 in.
Tooth-root radius:	± 0.011 in.
Tooth-tip radius:	± 0.011 in.

It should be emphasized that these are total variations in relatively large dimensions, not in in./in. These values compare very favorably, therefore, with other precision-casting processes.

Sprocket Heat Treatment

Pretreatment.—After casting, all test sprockets were heated to 1550°F, held two hours and furnace-cooled. This resulted in stress relief and a homogeneous structure for flame hardening.

Flame-Hardening.--All sprockets were flame-hardened by the Detroit Flame Hardening Company. A typical hardness survey of a new tooth is shown in Table V. The data are well within the specification for this part.

4. SERVICE PERFORMANCE

Cast sprockets were placed in comparative service tests with fabricated parts on the same tank at Milford, Michigan; Aberdeen, Maryland; Fort Stewart, Georgia; Fort Churchill, Canada; and Yuma, Arizona. The results of the tests to date are given in Table VI.

It is evident that the cast sprockets provided better service life in all cases shown. In another instance, Fort Stewart, Georgia, an unexpected wear pattern was encountered as illustrated in Fig. 8. The peculiar clay and angular quartz soil in the Georgia installation resulted in the unusual pattern. The highly abrasive quartz-clay mixture packs beneath the track and remains on the sprocket. This condition was easily remedied by a small change in the flame-hardening treatment and castings prepared in this manner are being tested.

In general, the superior performance of the cast material is ascribed to the following causes:

(a) fine grain structure and lack of the banding which is encountered in the fabricated sprockets (Fig. 9); and

(b) greater hardenability. Deep hardenability is not desired by the fabricator of flame-cut sprockets because of the possibility of cracking during torch-cutting.

The cast sprockets can be produced without trouble with any desired hardenability. In the cast sprocket both greater hardenability and absolute hardness can be obtained by increased carbon content, thereby saving critical alloys and reducing cost. Castings of this type are now being tested by Chrysler in another project which was initiated as a result of this work.

5. ADVANTAGES OF THE NEW METHOD

(a) Material conservation: The data of Table VII indicate a 48% yield in the case of the cast sprocket compared to a 26% yield for the fabricated sprocket. This is a very conservative calculation since it does not take into account the substantial material losses in passing from ingot to rolled plate.

(b) Lead time and production steps: The production steps for the cast sprocket are compared with the fabricated product in Fig. 10.

(c) Cost: The potential savings by use of the cast method are illustrated in Table VII. While these amounts cannot be expected in pilot production, they represent potential savings in full-scale production quantities in this and other vehicles.

(d) Material Specifications: In addition to inherent economies of precision-cast sprockets there is no limit with respect to steel specification. By casting, a steel of any desired hardenability can be produced as a longer wearing sprocket. To use higher hardenability steels for a fabricated sprocket would substantially increase cost, delay procurement and further reduce the yield. Procurement in particular would be a problem since 8600 and 4100 series steels are not normally produced in plate form.

II. DEVELOPMENT COMPLETED; UNDER TEST

A. Shell-Cast Ductile Iron Followers, Front and Rear, Parts Nos. 7359510 and 7360356

1. PURPOSE OF THE STUDY

The follower castings illustrated in Fig. 11 are used in the recoil mechanism of the 90-mm rifle of the M-48 tank. The present material (Spec. QQ-B-671-B) is cast aluminum bronze of the following composition

Cu:	83%
Al:	10-11.5%
Fe:	2-5.0%
Mn:	0.5%
Ni:	2.5%

This casting was selected for study for two reasons: (1) to determine if a noncritical ferrous alloy such as ductile iron could be substituted for the more expensive aluminum bronze, and (2) to investigate the use of shell molding for a larger casting with heavy sections as well. At the time this project was initiated, the heaviest commercial casting was an automobile crankshaft (70 lb) with only 1-1/2 in. sections. This casting provides 3-4 in. sections, and the pouring weight is 170 lb for the front follower, No. 7360356.

2. THE PROCESS DEVELOPED

Ductile iron castings were produced successfully in shell molds, using the technique illustrated in Figs. 11, 12, and 13.

Mold Design

The mold design developed, which employs only one riser, is shown in Fig. 12. Various riser designs were employed in the investigation, but the one illustrated provided consistently satisfactory castings. The molds are produced on a commerical model Shell Process Company machine, Fig. 13. The shell-molding method is described below.

Sand-Resin Mix

94% sand
6% resin (by weight)
Solvent - 30% of resin content, 3 parts Ethyl or methyl alcohol, 1 part H_2O

Procedure for Mixing

Place sand in muller.
Add resin. Mix for 30 seconds.
Add solvent.
Mull until lumps are broken down to almost the original screen fineness.
Remove from muller and screen to aerate the mix.

Remarks

Over-mulling should be avoided, i.e., do not mull until the mix is thoroughly dry.

The coating is complete in approximately 3 minutes in a Simpson muller.

Further mulling serves to evaporate the solvent.

Air blown into the mix to accelerate the vaporization of the solvent should not be introduced until the coating of the sand grains is complete. A light stream is preferable; a heavy stream may tend to dry out the solvent in certain areas too rapidly, causing the resin on the sand grains to break away during the subsequent abrading of the sand grains.

The sand should be thoroughly dry before being placed in the investment chamber. Otherwise, it will tend to pack, reducing its flowability and causing a mold to be of poor quality.

Production Cycle

Preheat pattern to 450°F.
Spray pattern with release agent (Union Carbide LS-46 silicone).
Invest pattern for 13 sec. Remove to oven; cure for 60 sec at 700°F.
Repeat above cycle, then eject shell.
Shell thickness approximately 1/2 in.

Melting Practice

The melts were made in a 200-lb high-frequency induction furnace by a practice which provides casting properties duplicating those of standard commercial sources. Standard charge materials were employed and the melts were inoculated with 1-1/2% alloy addition of 9% magnesium cerium ferrosilicon following accepted commercial practice.

The shells were embedded in green sand and poured at 2550°F in 9 sec. After cleaning, inspecting, and cutting off risers, the castings were machined commercially.

3. PROPERTIES OF CASTINGS MADE BY THE NEW METHOD

The use of shell molds resulted in castings free from burnt-on sand and with good surface appearance. The experiments illustrate that ductile iron sections of 3-4 in. can be cast satisfactorily in shell molds.

The structure of the castings was determined metallographically and consisted of a matrix of 5-15% pearlite, 85-95% ferrite with spheroidal graphite (Fig. 14).

It was decided to use the as-cast structure for initial tests since it is the least expensive to obtain. Microscopic examination, chemical analysis, X-ray and cobalt-60 radiography were used to insure sound castings of the desired structure.

4. SERVICE PERFORMANCE

Firing tests were conducted at Erie Ordnance Dept., Port Clinton, Ohio, with the following conclusions.

Scoring of the follower castings by the gun tube took place. There was some pickup of metal by the gun tube; the scoring was confined to plastic flow of the ductile iron as illustrated in Fig. 14. The ferrite in the ductile iron was apparently too soft a structure for this application.

To avoid this effect, three new sets of followers have been prepared with the following characteristics:

Matrix - 90-98% pearlite, balance ferrite and spheroidal graphite (Fig. 15).
Surface coating to assist in break-in and avoid scoring:
  (a) Teflon-coated; the Teflon is bonded with DJ-855 phenolic resin by baking at 300°F, 1 hr.
  (b) Tin-plated - Type I, Spec. Mil-T-10727.
  (c) No surface coating, normalized heat treatment.

5. ADVANTAGES OF THE NEW METHOD

The results of these tests should be available within two months to permit a final evaluation of the new method of production. In any event, the experiments indicate a satisfactory shell-molding technique for heavy sections of ductile iron.

B. Precision-Cast Final Drive Gear, No. 7364141

1. PURPOSE OF THE STUDY

The purpose of this work was to determine whether final drive gears (Fig. 16) could be cast accurately by the permanent mold technique and thereby eliminate the rough machining operations now required. If successful, substantial savings in material, expensive machining equipment, and lead time, as well as greater flexibility in analysis can be achieved. Present gears are machined from AISI 4817 forged blanks and carburized. In these experiments cast gears of this material were made, machined, and carburized. In addition, advantage was taken of the precision-casting method to produce other gears of AISI 1062 for finish-machining and rapid induction-hardening, thereby eliminating carburizing.

2. THE PROCESS DEVELOPED

The method used for gear production is somewhat similar to that used for sprockets and therefore does not require detailed description. This work was done under subcontract by the Griffin Wheel Company. Graphite molds were used for the body of the mold, and gray-iron inserts were machined for the teeth. Full details of the mold assembly are given in Fig. 17.

Following preliminary work and the recommendations of the Brad Foote Gear Company, the following stock was allowed on the teeth:

(a) For carburized AISI 4817 gears, 0.060-0.070 in.
(b) For induction-hardened AISI 1062 gears, 0.030-0.040 in.

Ten gears of AISI 4817 and eighteen gears of AISI 1062 were produced for shipment.

Table VIII contains a summary of all experimental castings produced during this investigation and their final disposition. Table IX contains the chemical analysis of all test castings.

It should be noted that the rough cut prior to carburizing on castings Nos. 62, 66, 69, and 70 resulted in insufficient stock after carburizing. The special quench and temper pretreatment used for forging blanks was not specified for precision castings and was the cause of the loss of these four gears. Proper pretreatment or modified machining procedures will eliminate this problem.

Figure 18 is a photograph of an as-cast AISI 1062 final drive gear prior to any machining operations. Figure 19 is a photograph of an AISI 4817 cast gear after maching and carburizing, together with its mating pinion. The excellent surface and detail are obvious.

Tables X, XI, and XII contain the summaries of all dimensional studies made on these cast gears. These data include pin-diameter measurements in Tables X and XI, and in Table XII:

A-1 through A-4: plate thickness,
J-1 and J-2: hub diameter,
L-1 and L-2: outside diameter, and
P-1 through P-4: pin thickness.

Appendix A contains both the data from which these summary tables were derived and a detailed discussion of the statistical analysis performed by the Griffin Wheel Company.

Table VIII, the heat and casting summary, shows a great number of castings which were considered unacceptable due to an apparent cold-metal wrinkle on one or more teeth. Although this condition was improved somewhat when the mold tilt angle was changed from 3-1/2° to 2°, the loss was still considerable. For accurate evaluation, a gear casting with a typical wrinkle was machined to determine the depth of the defect. Pin-diameter measurements indicated an average of .030-in. stock on the tooth surface. Inspection of the finish-machined gear indicated that an additional .030 in. would have reduced the scrap loss to 5%.

Limitation of the graphite-mold and pressure-pouring process was defined by statistical analysis of measurements taken from 37 gear castings. Rim, plate, and hub dimensions were all within practical requirements as designed. Stock on the surface of the teeth was found to be inadequate, as originally designed. Data showed that a minimum of .060-in. stock should be provided on the face of each tooth to compensate for surface blemishes. Differences in pin-diameter measurements due to process variations were defined as ± .032 in. at the 95% confidence level. Use of these figures makes it possible to design a gear casting which might be produced on a practical production basis, to define the accuracy of the casting, and to specify the amount of stock provided for machining.

Reaction of the gears to the hardening treatment has indicated that investigation of procedures for pre-heat-treatment of the casting before carburizing or induction-hardening would be worth while.

3. ADVANTAGES OF THE NEW METHOD

This development, together with that of the sprocket, indicates that any desired steel analysis can be poured in graphite molds. There is no appreciable carburization of the steel by the graphite mold as determined by careful metallographic inspection at 1000 diameters.

The gear castings indicate further that sections up to 3 in. can be cast accurately and with excellent surface finish. The grain structure of the cast gears will be free from any banding or other forging defects and should provide equivalent or better service. The precise casting operation eliminates a lengthy and expensive rough-hobbing operation of approximately two hours.

Furthermore, if the unalloyed induction-hardened AISI 1062 gears are successful, a marked saving in critical materials will be realized.

III. ENGINEERING AND DESIGN COMPLETED; READY FOR PRODUCTION OF TEST CASTINGS

A. Precision-Cast Crankshaft for AV-1790 Engine, No. 8717036

1. PURPOSE OF THE STUDY

One of the outstanding advances in design and cost reduction of components for automobile engines has been accomplished by the use of precision-cast crank-shafts. By the replacement of wrought parts, greater flexibility of design and reduction in machining has been possible. It was natural, therefor, to consider the higher-performance alloy-steel crankshaft of the AV-1790 tank engine, which is 350% heavier than the automotive shaft, as a proper subject for engineering study.

The AV-1790 tank-engine crankshaft poses many more difficult problems than automobile crankshafts, which are cast in malleable or ductile iron in relatively light sections. Shell-molding techniques are available for this work. By contrast, the high-performance AV-1790 engine requires an alloy-steel crankshaft cast in heavy sections. No techniques were available for economical precision castings of this type at the start of the project. It now appears, however, that the part may be precision-cast through new technique developed on other components and in supplementary research.

In the meantime, the critical sections of the crankshaft (journal and bearings) have been cast, subjected to stress analysis and redesigned. The excellent cooperation of the Continental Aviation and Engineering Corporation in the design and stress analysis work is gratefully acknowledged. A new, very promising design for casting has been developed.

2. THE PROCESS DEVELOPED

Since this phase of the project has just passed the design stage, no complete crankshafts have yet been made. Discussion will, therefore, be confined to the production and testing of critical sections.

The present forged and machined design is illustrated in Fig. 20. The design changes to take advantage of the casting process are illustrated in Fig. 20 and in the model of Fig. 21.

Castings of the model were made of AISI 4340 steel using merely a good dry-sand molding technique. These provided test sections for stress analysis and were not intented as precision castings.

Previous work at Continental Aviation and Engineering Corporation had proved that torsion was not critical and that bending stress was the important consideration. It was possible, therefore, to work with single-throw sections of the complete shaft.

Following the accepted methods of stress analysis, the regions of highest stress were first located with stresscoat, and then resistance-type strain gages were employed for more accurate measurements.

The manner of loading the test section is illustrated in Fig. 22. This procedure was developed in previous CAC research.

The stresscoat indications comparing the forged vs. the cast designs are shown in Figs. 23 and 24. The maximum strain in the cast design is reduced to 575 µin./in. compared with 66[illegible] µin./in. in the forged design--a reduction of 14.2% at a bending moment of [illegible]. Equivalent percentage reductions are obtained at other stresses in the elastic range. These data were obtained with SR-4 resistance strain gages as shown in Fig. 25.

Additional determinations were made to find out if the hole in the crank cheek could be enlarged to simplify casting procedures. The data from these tests indicated a 7/8-in.-diameter hole can be used in place of the present 1/2-in. hole if desired.

The CAC investigation pointed out that still further improvement could be obtained by modification of the re-entrant fillets.

3. ADVANTAGES OF THE NEW METHOD

The engineering study just described indicates that full-size cast crankshafts should be made and tested because of the following advantages.

(a) Reductions in cost and in use of critical machine tools

In Fig. 26 the surfaces requiring machining on the cast crankshaft are the important bearing surfaces which are relatively simple to finish. The tedious and expensive drilling of holes through the journals and the machining of the counterweignts has been eliminated.

Again it should be emphasized that the design principles developed for this shaft may be readily applied to any other similar shaft (after investigating principal production methods and confirmation by the full-scale tests projected for this engine).

(b) Reduction in lead time, complex machining, flexibility of analysis, and saving in critical material

In many cases substantial delays are encountered because of shortages of quality steel billet stock such as AISI 4340. These can be circumvented by passing directly from raw materials to castings. In addition, other alloys may be easily substituted when desired in this process. As also shown by Table XIII a 13% increase in yield of critical material will result from the casting process. The elimination of complex machining, such as the special equipment needed for drilling of the crank pin holes in line for 5 ft, is also an important production advantage.

(c) Stress reduction

The substantial reduction in operating stresses in critical locations can be used either for lighter design or for greater safety under severe conditions such as fatigue.

In view of these pronounced advantages, it is strongly recommended that provision in future work be made for manufacture and testing of precision-cast crankshafts.

B. Crankcase for AV-1790 Engine

1. PURPOSE OF THE STUDY

The requirements for greater load-carrying ability in the crankcase sections have led to very heavy (4-in.-thick) designs. Because of the porosity and shrinkage encountered in sections of this size in the alloy used, only very low design stresses (3500 psi) are possible.

It is believed that a lighter, stronger crankcase can be made in either ductile iron or steel, utilizing the much higher, reliable design stresses for these materials, particularly in lighter sections.

With this end in mind the crankcase was redesigned.

2. THE DESIGN DEVELOPED

Since this study reached only the design stage, no actual experimental castings were produced. The present cast aluminum crankcase is shown in Fig. 27a and b. Figure 28 shows the cross section of the present crankcase and the new design for ferrous alloys. The lighter design of the new crankcase is evident from the drawings. A pattern of a section of the new design has been constructed.

It is recommended that this section be cast in steel and subjected to stress analysis before proceeding to full-size castings. An additional advantage of the new design is that repetitive segments could be cast individually and welded together. This would simplify casting production and inspection.

It was decided to leave further crankcase development to the manufacturer since precision castings were not required. The Superior Steel Casting Company can produce and weld the cast sections.

IV. UNDER ENGINEERING STUDY

As the earlier studies have progressed, the new techniques which have been developed have led to the reconsideration of several parts previously considered too complex for immediate action. These new parts include:

(A) Suspension and spindle arm, No. DTA 15910-15;
(B) Outer race ring, No. 7384006; and
(C) Cupola, No. C 8671475.

A. Suspension and Spindle Arm, No. DTA 15910-15

This complex fabricated component is illustrated in Fig. 29. Since it must be made at present as a large forging and weldment, the production is quite complex and cumbersome. With the cooperation of the Research Laboratory of the American Steel Foundries, and at no expense to the Government, a simple redesign has been evolved. The very heavy 4-by-4-in. solid section in the main arm can be converted to a lighter box section by coring of the casting.

It is anticipated that, by the use of advanced shell-molding technique and the development of the proper shell-mold assembly, this part can be produced as a single steel casting. This will eliminate the problem of pressing the spindle as well as the subsequent alignment problems in service.

The savings in lead time, cost, and weight of critical materials should be very substantial.

B. Outer Race, No. 7384006

This component (Fig. 30) is now made by extensive machining of a forged ring of AISI 4150 steel. The internal gear is then hardened by flame- or induction-hardening techniques.

It is proposed to develop in place of this complex forging a precision casting using combined graphite-mold and ceramic-core techniques. The problem is more advanced than that of the sprocket because of the greater size (8-ft diameter) and because the teeth are internal. The successful solution of this problem would then permit the use of the graphite-permanent-mold technique for practically any gear or sprocket shape. The advantages should be at least as great as those demonstrated for the sprocket.

An alternate method, employing separately cast segments, is also under study at the present time.

C. Cupola, No. C8671475

This part is now made as a steel casting. Because of the heavy sections, the part is subject to such defects as burnt-on sand related to the mold-metal interface reaction discussed later in this report. Furthermore in large castings of this type, considerable finishing is required to obtain the required dimensions.

It is proposed to obtain better mechanical properties and closer dimensional tolerances by employing permanent-mold techniques. The rapid freezing coupled with the relatively inert mold surface should be very effective in accomplishing this result. Design modifications, such as elimination of projections which lead to hot tears, are also contemplated.

CONCLUSIONS: RECOMMENDATIONS FOR FUTURE WORK

Based upon the data of the individual studies which have been summarized in this report, the following conclusions are justified:

(1) The use of precision castings in an appreciable number of ordnance components results in substantial savings in cost, critical materials, and lead time, and to reduced use of critical machining and fabricating equipment.
(2) Greater flexibility in design and better stress distribution and load-carrying ability can be achieved in cast designs than are possible with fabricated assemblies.
(3) The development of alternate specifications and production methods greatly augments the number of commercial sources available in time of emergency.

It is recommended, therefore, that this development of precision castings for ordnance be continued along the lines indicated in this report to include particularly the crankshaft, the suspension and spindle arm, and other vital components.

It should be evident from the extensive work described in the text that these studies are not at all routine but require the fullest development effort of the group of industrial and university personnel which has been assembled. In other words, the original thought of Ordnance Tank-Automotive Command—namely, that the proper application of precision-casting processes for ordnance poses many problems requiring special development effort—seems adequately confirmed. It is confidently anticipated that future effort along those lines will be even more rewarding.

APPENDIX A

APPENDIX A

DETAILED DISCUSSION OF STATISTICAL STUDY
PRECISION-CAST FINAL DRIVE GEAR, NO. 7364141
EXTRACTED FROM GRIFFIN WHEEL CO. FINAL REPORT

It is believed that a meaningful definition of the variation which might be expected in any lot of gears produced by pressure-pouring in graphite molds might be had by analysis of measurements taken from 37 castings produced on this project. Forty-five specific measurements for each casting are shown on the data sheet accompanying this report. Analysis of pin diameters is considered to be the most pertinent due to the close dimensional control and freedom from defect specified on the gear teeth. Rim thickness, plate thickness, hub diameter, and outside diameter will also be discussed.

The 37 gear castings from which measurements were taken fall into two groups. Castings Nos. 17 through 54 were produced in two molds designed to produce castings having pin diameters large enough to provide approximately .030-in. finish on the surface of each tooth. Castings Nos. 58 through 70 were made in molds which had been enlarged to provide extra finish on the SAE 4817 gear castings. All dimensions other than pin diameter were the same for both lots.

The 33 pin diameters for each casting in the group Nos. 17 through 54 were measured and recorded on the data sheet. The mean and standard deviation of the 33 diameters of each casting were then calculated and are presented in Table X. The mean pin diameters of each casting were then averaged and the standard deviation was calculated. These values also appear in Table X. The same procedure was applied to the measurements taken from the second group, castings Nos. 58 through 70, and recorded in Table XI.

The standard deviation of the individual casting mean diameters and the average of the standard deviation values for the individual casting were found to be identical for both groups. The similarity of these figures is an indication of the accuracy which might be expected in relation to different products of generally similar size.

The data presented in Tables X and XI also allow a statistical evaluation of the uniformity of the graphite-mold and pressure-pouring process in relation to the final drive gear. Using a confidence level of ± 2 standard deviations from the mean, it can be stated that, if similar samples of gear casting were studied, 95% of the mean pin diameters of individual castings would not vary more than ± .012 in. Going further, 95% of the individual mean pin diameters would not vary from the arithmetic average of the individual means by more than ± .020 in. If the variation of the average of individual mean pin diameters is then corrected by the amount of tooth-to-tooth variation of the individual casting, the total error which might be expected at the 95% confidence level becomes ± .032 in. or a range of .064 in. If this value is added to a theoretical pin diameter calculated to provide .060-in. finish on the surface of each tooth, it becomes possible to design a casting which has sufficient stock to compensate for process variations and surface defects. Recommended pin diameter for future production of Ordnance part No. 7364141, using pressure-pouring in graphite molds, is 20.034 in. and is calculated from the data presented as follows:

Finish pin diameter	+	base stock per tooth	+	process variation	=	recommended design
19.730	+	4(.060 in.)	+	.064 in.	=	20.034 in.

Also calculated and shown in Tables X and XI is the average amount of stock on the tooth surfaces of the individual castings produced on this project. This figure is obtained by dividing the difference of the mean pin diameter and theoretical pin diameter by 4. It will be noted that for the entire lot of 25 castings the average stock is .027 in. The chiller ring used to produce this group was designed to produce .030-in. stock, indicating a design error of only .003 in. Since time was short, the same gear-cutting tool was used to enlarge the molds which were used to produce castings Nos. 58 through 70. Although the outside diameter of the casting was increased over .100 in., Table XI shows an average increase of tooth-surface stock from .021 to .048 in., thus falling .012 in. short of the desired figure.

The dimensions for rim thickness and plate thickness have specified tolerances of ± 1/32 or .031 in. Table XII lists the arithmetic mean of the measurements taken at these locations from the sample of 37 castings. The mean plate thickness was found to be .870 in. with a standard deviation of .009 in. Comparing these values to the specified .875 in. ± .031 in., it is determined that under similar conditions there is a chance of less than three castings in a thousand (± 3 standard deviations) falling outside the specified range of from .844 to .906 in. Mean rim thickness determined from the 37 castings measured was 3.249 in. with a standard deviation of .007 in. Adding .010-in. stock for correction of parallelism errors, these values indicate that rim-thickness variation in similar samples would still be within the 2.219- to 2.281-in. range specified.

Variation of rim thickness can be caused by foreign particles at the mold parting line, whereas uniformity of plate thickness can be affected by inaccuracies in machining and subsequent remachining of the graphite mold. Both can be affected by variation in thickness of the refractory coating put on the mold.

Hub-diameter variation, given in Table XII, is of the same magnitude as reported for plate and rim thickness, and is well within the requirements for this area.

Outside diameter was measured at only two locations on each casting. This measurement was difficult to obtain because the small amount of surface on the tooth tip did not afford accurate positioning points for the measuring instruments. Because of this it is believed the data obtained are not a true measure of the process.

It is submitted that the foregoing information, documented by the data presented in the accompanying charts and illustrations, defines the limitations of the process in relation to casting design and product uniformity and proves the feasibility of producing the final drive gear by pressure-pouring in graphite molds.

APPENDIX B

APPENDIX B

SUPPLEMENTARY EXPERIMENTAL WORK

In addition to the development of technique for specific parts, supplementary investigations whose results have wide application were performed. This effect may be summarized now under two principal studies.

(1) Effects of Mechanical Clamping of Shell Molds on Improving Dimensional Tolerances

PURPOSE OF THE STUDY

The problem of dimensional accuracy in shell molds is not merely a function of proper design of the pattern and of molding technique. Bulging, particularly of flat surfaces can be encountered during solidification and can lead to inaccurate dimensions. One of the first castings in which this was noted was the follower, discussed in Section IIA. Representative measurements showing distortion of as great as 0.033 in. are indicated in Table XIV. Conventional methods of gluing the shells, weighting with metal shot, or ramming in place with green sand did not improve this condition.

Although this problem seemed most important with graphitic materials, it was decided to investigate cast steel as well as gray and ductile iron in a quantitative manner. A step test bar which had been developed for dimensional studies in previous research was selected (Fig. 31). Castings were poured from induction-melted heats of the following aim analysis:

	% C	% Mn	% P	% S	% Si	% Mg
Gray iron	3.60	0.30	0.05	0.05	2.20	
Ductile iron	3.60	0.30	0.05	0.01	2.20	0.05
Cast steel	0.25	0.30	0.05	0.05	0.30	

Melting practice followed procedures already discussed.

The shell molds were subjected to different backing procedures. In addition, some molds were made by the "CO_2 process" in which a very hard mold is produced by a silica bond.

Dead-weight types of backing included metal shot (Fig. 32), green sand, iron weights, and sand, plus weights-all conventional foundry procedures.

A new method was developed using dynamic backup by employing calibrated spring clamps as illustrated in Fig. 33. The shell was ground to fit the steel bars and the end springs were set to the desired load.

The three different alloys were first cast in the conventionally backed molds with the results shown in Tables XV, XVI, and XVII. In these experiments the variations in the thickness of the large step may be summarized:

	- deviation (in.) to	+ deviation (in.)
Gray iron	- 0.002	+ 0.004
Ductile iron	+ 0.015	+ 0.053
Steel	- 0.007	+ 0.023

Since the greatest problem and most consistent bulging encountered with ductile iron, further work was confined to this material. The effects of conventional weighting techniques and the new spring clamping may now be discussed.

Changes in conventional weighting techniques or the use of very hard CO_2 molds had little effect upon bulging. In contrast, the data of Table II indicate reliable and consistent improvement by using the dynamic clamping method.

The graph of Fig. 34, based on the data of Table XVII, indicates the decrease in bulge with applied spring pressure. At a total force of 240 lb, no bulging was encountered. It is also evident that the dimension "A" at the end of the step was less than for the conventionally weighted castings. In other words, ordinarily the entire casting bulges due to graphite precipitation in the final phases of solidification, but the reaction is more pronounced at the center due to the hot spot.

CORRELATION OF RISERING WITH BULGING

In all the castings discussed so far, the risering was adequate to prevent shrinkage defects. However, a question arose from the preceding data concerning the effect of clamping upon feed-metal requirements: if a casting is clamped to prevent bulging, would not the feed-metal requirements be reduced? If so, higher casting yields as well as greater precision could be expected from rigidly clamped molds.

To test this theory, the riser sections of test molds were stopped off and a narrow runner was provided from the downsprue. A series of riserless ductile iron castings was then poured with different spring loading. The density of the castings was then measured and plotted vs. the amount of bulge (Fig. 34). Extrapolating the graph to zero bulge, the line approaches the density of a completely sound, risered casting, A20-3.

While this phase of the program represents only a preliminary study, the following facts are established:

(a) Control of bulging will reduce risering requirements.
(b) In riserless castings that are nearly sound, clamping may produce complete soundness.
(c) The problem of bulging can be serious in small ductile iron castings. It also seems reasonable to suggest that large shell castings of any type, even if the metal is skin-forming, will be subject to bulging.
(d) Normal variations in pouring temperature have little or no effect.
(e) A rigid type of mold backing does not supply sufficient protection.
(f) The means of controlling bulging have been developed. Dynamic steel clamps employing springs to provide restraining force will give excellent results. The necessary number of clamps and forces will vary with the application.

(2) Surface Quality and the Role of Mold-Metal Interface Reactions

PURPOSE OF THE STUDY

Even though very accurate patterns and molds are produced, there is no assurance that accurate castings will result unless the reaction of the molten metal with the mold surface is under control. To control and minimize the mold-metal interface reaction, it is first necessary to understand what is occurring. Two important investigations bearing on this problem will be reviewed: the iron-silica interface reaction, and reaction of silica with iron-carbon alloys. The first is of considerable importance in understanding and improving the surface of steel castings; the second involves cast iron and ductile iron.

THE IRON-SILICA INTERFACE REACTION

The quality of the surface as well as the dimensional accuracy of a casting depends on the extent of the reaction between the metal and the mold material. Some of the variables affecting the reaction are the compositions of metal and sand, pouring temperature and casting cooling rate, metal pressure, and the mold atmosphere.

The system iron-silicon-oxygen-carbon was chosen for study because iron and silica and a gaseous atmosphere are the principal reactants in the mold-metal interface reactions. Once the mechanism of a simple system is known, the effects of additional elements may be explored.

Each specimen consisted of a mixture of reagent-grade iron powder and quartz grains (Ottawa silica sand, 40-60) contained in platinum envelopes. Heating was done in a horizontal globar furnace. The degree of oxidation was controlled by premixing CO and CO_2 gases in desired ratios. The partial pressure of oxygen may be calculated from the known equilibrium constant of the equation $CO + 1/2\ O_2 = CO_2$.

In addition to providing a convenient control of the oxidation level, both CO and CO_2 are present in mold atmospheres. Furthermore, other atmospheres containing hydrocarbons and oxygen may be expressed in terms of equivalent CO_2/CO atmospheres.

The gas mixtures were analyzed with a mass spectrometer. After exposing the specimens for the desired periods of time, 3 min to 1 hr, they were cooled by pushing them into the cold end of the furnace while maintaining the same atmosphere.

X-ray and metallographic samples were prepared. The latter were impregnated with bakelite resin (BR-0014) prior to mounting and polishing for metallographic examination.

The various treatments are summarized in Table XVIII. It should be noted that two of the temperatures, 1225°C (2237°F) and 1525°C (2777°F), are below the melting point of pure iron, 1537°C (2802°F). However, 1525°C (2777°F) is at the melting temperature of oxygen-saturated iron.

The data indicate that the mechanism of mold attack in this system is as follows. Iron is oxidized at the mold surface, forming a separate, oxide liquid which wets the silica sand in the mold. This liquid phase penetrates into the pores of the mold. Silica is soluble in this oxide liquid to about 50 weight-percent. Solution of the silica enlarges the pores in the sand. This enlargement permits the molten iron to penetrate the mold at low pressures although the iron does not wet the silica sand. The depth of penetration into the sand by the iron depends on the length of time at elevated temperatures and the severity of oxidation.

If the CO_2/CO ratio is maintained at a low level, only quartz grains and iron are present. No iron silicate melt is observed and no penetration occurs at low pressures because the iron does not wet the silica.

Thus surface deterioration continues after solidification. The more rapid the cooling or the more reducing the mold atmospheres, the better the surface that can be expected. This indicates the basic superiority of the graphite semi-permanent mold process with its rapid cooling and tendency toward reducing mold atmospheres. When a mold surface of quartz or other sand is to be used, it is evident that surface oxidation should be avoided by suitable additions to metal or to mold materials.

REACTION OF SILICA WITH IRON-CARBON ALLOYS

The surfaces of large shell-molded iron castings are more subject to imperfections than are the surfaces of smaller castings. An important potential difficulty arises when large iron castings are made in silica shell molds because some of the silica may be reduced to SiO by certain alloying elements in the molten iron. This surface defect is shown in Fig. 35.

The SiO which is formed is a gas at ferrous casting temperatures. As a result, its formation at the metal-mold interface of the casting provides a porous surface if the gas cannot escape from the mold. As the temperature decreases, the SiO dissociates to SiO_2 according to the reaction:

$$2\ SiO \longrightarrow SiO_2 + \underline{Si} \qquad (1)$$

Therefore, the porous metal surface generally contains an SiO_2 deposit.

This report presents information concerning the nature and extent of the SiO_2 reduction at the mold-metal interface. The roles of temperature, casting size, alloys, and selected mold materials were investigated to interpret the mechanism of the reactions. On the basis of the results, methods of minimizing the effects are suggested.

EXPERIMENTAL PROCEDURES

Mold Design.—Three mold designs were used in this investigation: (1) a small step mold, (2) a small gear-blank mold, and (3) a large step mold. The step mold designs are shown in Figs 31 and 36. With these designs, it was hoped to determine the effects of mold volume, section thickness, and parasite section upon the interface reaction.

The small step mold has a volume of 19.21 cu in. with an additional 37.95 cu in. in the riser, gates and sprue. The heaviest section is 5 in. by 1 in. by 2 in. thick. The thinnest section is 2-1/2 in. by 1 in. by 1/16 in. The gear-blank mold consisted of three gear blanks with a total volume of 42.25 cu in. The casting was poured through the riser. The heaviest section was a ring 3 in. in diameter, 1 in. wide, and 1 in. thick. The large step mold had a volume of 300 cu in. with an additional 225 cu in. in gates, riser, and sprue. The largest section was 8 in. square by 4 in. thick. The total parasite volume was 43 cu in. and the smallest section was 4 in. by 1 in. by 1/8 in.

Shell molds were made over the patterns described in the preceding paragraph. The sands used were: (1) two kinds of quartz sands, Geauga sand, and New Jersey beach sand; (2) forsterite sand; (3) Australian zircon sand; and (4) magnorite. Both the forsterite and the magnorite sands contained an excess of fines as received. The excess fines were removed by elutriation. All molds were made with coated sands. Six percent of resin by weight was used with all sands except the zircon which had 3% by weight of resin.

Metal Compositions.—The metal compositions used were essentially iron-carbon alloys (1-4% carbon) which contained less than 0.05% of silicon and manganese. Other heats were made containing 0.5% silicon and 0.5% manganese to determine what, if any, effect these elements would have upon the reactions.

In the first group of heats, aluminum in the amount of approximately 0.1% was added in the furnace and in the ladle to keep the oxygen level low and to control the carbon boil. No aluminum or other deoxidizer was used in the second group of heats. Instead, the surface of the metal in the furnace and in the ladle was completely covered with a basic slag.

The large castings were poured directly from the furnace into the mold to minimize oxidation and to facilitate the control of casting temperatures. The basic slag was successful in preventing oxidation of the heat. The heats were made in either a 60-lb-capacity or a 200-lb-capacity induction furnace with rammed magnorite linings. The stock was armco iron, and spectroscopic grade graphite electrode as the source of carbon. Carbon levels ranged from 4% to 1% in steps of 0.5%. Casting temperatures ranged from 3000°F to 2500°F in steps of 100°F.

RESULTS

The defects shown in Fig. 35 consisted of porosity in the metal at the surface of the casting. The gas pockets contained an accumulation of white powdery material which was identified spectroscopically and optically as SiO_2 and Al_2O_3. Optical and electron micrographs revealed that the former had an extremely fine-grained fibrous structure. It is of prime importance that X-ray and electron diffraction patterns indicated a significant fraction of the fibrous material to be quartz. Furthermore, quartz was the only crystalline silica phase which was observed. The importance of this observation is that quartz is stable, and will form only below 1600°F. Had the SiO_2 crystallized at a higher temperature, the tridymite and cristobalite modifications of silica would have been observed since they do not transform to quartz in the short period of time that is encountered during normal cooling of the casting.

The defects shown in Fig. 35 were the most pronounced under conditions of (1) greater super-heat, (2) larger metal sections, (3) higher carbon contents, (4) with the presence of aluminum, and (5) in molds with a large amount of free silica. Individual consideration of these variables will show their relative effect.

Effect of Temperature.--In a 4% carbon, 0.1% aluminum casting, the defects which have been described were not encountered at temperatures below 2550°F. As the pouring temperatures were increased, the gas pockets and the accompanying SiO_2 deposits were more pronounced. This same general increase with temperature was noted for all metal compositions.

Effect of Section Size.--With comparable carbon contents and with silica sand, the defects first appeared in the 19-cu-in. castings with 1-in.-thick sections at temperatures of about 200-300°F higher than that in the 300-cu-in. casting with 4-in.-thick sections.

Effect of Carbon Content.--Other factors being equal, these defects were more pronounced with higher carbon contents. For example, a 1% carbon, 0.1% aluminum casting does not produce surface porosity even at 3000°F, whereas the defect occurs at a temperature as low as 2550°F when 4% carbon is present.

Effect of Alloy Additions.--Aluminum additions to the molten metal have a more pronounced effect upon the defect than carbon. With 0.1% aluminum, the lowest temperature at which the defect was encountered in a 4% carbon melt was 2550°F. With no aluminum, the defect was not encountered at 3000°F.

Silicon and manganese additions up to 0.5% did not have any noticeable effect upon the presence or absence of the gas porosity and the SiO_2 deposits at the surface of the castings.

Effect of Mold Compositions.--The described defect is most pronounced in a silica-sand shell mold. In shell molds of forsterite (Mg_2SiO_4), zircon ($ZrSiO_4$), or periclase (MgO containing 10% SiO_2), defects were produced only when other factors were adverse, with high casting temperatures, large section sizes, high carbon, and the presence of aluminum.

The effect of mold composition is especially notable in the smaller castings. When a 4% carbon iron containing 0.1% of aluminum was cast at 2900°F into the small gear-blank mold made of zircon sand, little porosity was produced. When iron of the same composition was cast at the same temperature into the large step mold made of zircon sand, a condition similar to that shown in Fig. 35 was observed. With silica sand the defect was found in both large and small castings.

DISCUSSION

The surface defects must originate from reactions involving silicon and oxygen. This is supported by the facts that (1) silica shells provided the most severe effects, and (2) and SiO_2 deposit is produced. At least three hypotheses may be considered to account for reactions between the silicon and oxygen.

The first possible mechanism would involve the oxidation of silicon in the metal to produce SiO_2 in the gas pockets. Silicon oxidation is observed in higher silicon steels. However, gas porosity does not result. The resulting SiO_2 forms a liquid at temperatures above 1600°F. Furthermore, a silicon addition to the metal in this case had no noticeable effect upon the presence or absence of the defects. The possibility of this mechanism must be discounted for these castings.

A second possible reaction mechanism would involve the reduction of SiO_2 in the sand by heated resins in the shell to produce an initial gas containing SiO. Although well known in chemistry, SiO is relatively unknown in metallurgy.

$$xSiO_2 + C_xH_{2y} \; . \; . \; . \; . \; . \; SiO + xCO + yH_2 \qquad (2)$$

This reaction would require a pressure accumulation at the surface of the metal during solidification. There is some evidence to suggest that the contact of the molten metal softens the bonding resin behind the mold surface and clogs the pores in the sand. This produces an impermeable sand which will permit such pressure to build up. Under this mechanism, the SiO would revert at lower temperatures to SiO_2. Thermodynamic considerations favor this reversal.

The plausibility of this second suggested mechanism is greater than that of the first. Higher temperatures would increase the reaction by producing more SiO and more gas pressure. Likewise, larger castings would accentuate the results by providing longer cooling times. However, it is difficult to account for the significant effect of carbon and aluminum upon the presence of the defects.

The third possible reaction also involves the reduction of the SiO_2 in the sand, but by the carbon and aluminum in the metal:

$$C + SiO_2 \; . \; . \; . \; . \; . \; CO + SiO \qquad (3)$$

$$2Al + 3\,SiO_2 \; . \; . \; . \; . \; . \; Al_2O_3 + 3\,SiO \qquad (4)$$

Aside from the fact that the reducing agents come from the metal rather than from the resins, this mechanism is similar to the previously suggested one. Both of the reactions occur more strongly at higher temperatures. Both produce SiO and require a retention of the gas by pressure at the mold-metal surface until dissociation occurs at lower temperatures to produce SiO_2.*

$$2\ SiO \ .\ .\ .\ .\ .\ SiO_2 + \underline{Si} \qquad (1)$$

Most probably the true mechanism requires both the reducing action of alloys within the metal and the protective reducing gases of the heated resins. Otherwise, the SiO would diffuse into the mold where it would oxidize with infiltrating air.

The avoidance of these defects may be suggested directly from the results of the tests. This would involve a minimum of super-heat, and avoidance of aluminum (and probably titanium and zirconium) in the metal, and in large castings the use of sands without free silica.

CONCLUSIONS

Although the reduction of SiO_2 to a gaseous SiO form by carbon and other elements has been known for some time, its importance in the control of surface quality of ferrous castings has not been generally appreciated. When conditions involving high carbon contents, the presence of aluminum or other strong oxide formers, high temperatures, or large mold sizes are encountered, SiO_2 will be reduced to SiO when iron is cast into molds containing quartz or silicate sands. The SiO, even though it is in the form of a gas, does not always escape from the mold cavity and may produce a surface porosity. Lower temperatures permit the dissociation of SiO to SiO_2.

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*Equation (1) is exothermic; therefore, it occurs more strongly to the right at lower temperatures.

APPENDIX C

APPENDIX C

DETAILED PROCESS DESCRIPTION

(1) Pressure-Poured Precision-Cast Drive Sprocket, Part No. 8671597

1. Machine the graphite mold according to drawings.

2. Complete required mold components, i.e., chiller ring, ingate sleeve, mold retainers, according to drawings.

3. Machine pattern for mounting bolt hole shell cores according to drawings.

4. Make required quantity of shell core from zircon sand.

5. Heat mold cope and drag and spray with expendable refractory coating.

6. Set shell cores and assemble mold.

7. Melt a heat of the required analysis.

8. Tap heat at the required temperature (determined experimentally during project).

9. Place ladle in pressure pouring tank and record molten metal bath temperature using immersion thermocouple.

10. When proper metal temperature is reached, a properly preheated pouring tube is positioned over the pouring tank and clamped in place.

11. The assembled mold is positioned over the pouring tube and clamped in place.

12. Pouring is then started and the mold filled at the experimentally determined rate (details previously reported).

13. After completion of pour, the mold is released from the pouring station and the casting stripped from the mold after a suitable time (details previously reported).

14. The hub is torch cut to a diameter leaving approximately 1/4" for finish machining.

15. Casting is placed in heat treat furnace and annealed.

16. The mold is cleaned, reconditioned and reassembled for further use.

17. Casting is cooled to room temperature after annealing and shot blasted to remove scale.

18. The hub is then bored according to drawing requirements.

19. Casting is flame hardened according to specifications, inspected, and is then considered complete.

(2) Precision-Cast Final Drive Gear, No. 7364141

1. Machine the graphite mold according to drawings.

2. Complete required mold components, i.e., chiller ring, ingate sleeve, mold retainers, according to drawings.

3. Heat mold cope and drag and spray with expendable refractory coating.

4. Set shell cores and assemble mold.

5. Melt a heat of the required analysis.

6. Tap heat at the required temperature (determined experimentally during project).

7. Place ladle in pressure pouring tank and record molten metal bath temperature using immersion thermocouple.

8. When proper metal temperature is reached, a properly preheated pouring tube is positioned over the pouring tank and clamped in place.

9. The assembled mold is positioned over the pouring tube and clamped in place.

10. Pouring is then started and the mold filled at the experimentally determined rate (details previously reported).

11. After completion of pour, the mold is released from the pouring station and the casting stripped from the mold after a suitable time (details previously reported).

12. The hub is torch cut to a diameter leaving approximately 1/4" for finish machining.

13. Casting is placed in heat treat furnace and annealed.

14. The mold is cleaned, reconditioned and reassembled for further use.

15. Casting is cooled to room temperature after annealing and shot blasted to remove scale.

16. The hub is then bored according to drawing requirements.

17. Casting is processed for carburizing or induction hardening as per instructions of Ordnance Tank-Automative Command.

TABLE I

CHEMICAL ANALYSIS - CASTINGS SUBMITTED FOR TEST
PRECISION-CAST DRIVE SPROCKET NO. 8671597

Heat No.	Sprocket No.	C	Si	Mn	P	S	Cr	Mo
R-179	35*	.50	.35	.79	.013	.024	1.08	.12
R-180	36	.51	.40	.82	.011	.020	1.07	.18
R-188	39	.51	.32	.90	.016	.028	1.08	.23
R-189	40	.50	.35	.84	.014	.021	1.03	.23
R-191	41	.53	.39	.94	.013	.028	1.08	.21
R-192	42	.52	.38	.87	.026	.030	1.08	.21
R-193	43	.51	.36	.88	.017	.016	1.04	.22
R-194	44	.51	.35	.82	.016	.026	1.05	.22
R-196	45	.53	.33	.81	.010	.030	1.08	.22
R-197	46	.51	.34	.90	.013	.024	1.07	.22
R-198	47	.53	.33	.75	.007	.026	1.05	.22
R-201	48*	.49	.36	.77	.012	.032	1.08	.23

*Shipped to Professor Flinn, The University of Michigan.
All others shipped to Detroit Flame Hardening Company.

TABLE II

PRECISION-CAST DRIVE SPROCKET, NO. 8671597
SPROCKET TOOTH-BASE WIDTH

Heat No.	Cast-ing No.	Tooth Numbers										
		1	2	3	4	5	6	7	8	9	10	11
R-179	35	4.258	4.254	4.253	4.257	4.255	4.251	4.243	4.241	4.245	4.240	4.248
R-180	36	4.260	4.250	4.247	4.250	4.248	4.247	4.236	4.235	4.242	4.244	4.255
R-181	37	4.262	4.250	4.250	4.250	4.247	4.248	4.234	4.235	4.238	4.241	4.260
R-188	39	4.261	4.250	4.249	4.252	4.252	4.250	4.245	4.241	4.247	4.249	4.256
R-189	40	4.262	4.257	4.249	4.251	4.250	4.252	4.246	4.243	4.241	4.250	4.257
R-191	41	4.263	4.254	4.249	4.249	4.247	4.248	4.243	4.240	4.244	4.247	4.256
R-192	42	4.257	4.250	4.250	4.250	4.250	4.253	4.244	4.245	4.245	4.249	4.253
R-193	43	4.264	4.250	4.245	4.248	4.247	4.248	4.243	4.238	4.241	4.245	4.252
R-194	44	4.262	4.250	4.246	4.250	4.244	4.246	4.237	4.238	4.241	4.247	4.254
R-196	45	4.263	4.255	4.248	4.252	4.250	4.253	4.243	4.242	4.244	4.250	4.255
R-197	46	4.263	4.258	4.254	4.254	4.250	4.248	4.242	4.239	4.244	4.250	4.258
R-198	47	4.264	4.254	4.250	4.255	4.253	4.256	4.244	4.245	4.244	4.249	4.256
R-201	48	4.268	4.253	4.250	4.253	4.250	4.251	4.248	4.245	4.246	4.254	4.256
Mean		4.262	4.253	4.249	4.252	4.250	4.250	4.242	4.240	4.243	4.247	4.255
Std. Dev.		.0027	.0028	.0034	.0026	.0028	.0028	.0039	.0033	.0024	.0038	.0038

Mean Standard Deviation: .0030 in.
Specified Dimension: 4.250 in.

TABLE III

PRECISION-CAST DRIVE SPROCKET, NO. 8671597
SPROCKET TOOTH-ROOT RADIUS

Heat No.	Casting No.	Tooth Numbers										
		1	2	3	4	5	6	7	8	9	10	11
R-179	35	9.873	9.877	9.878	9.882	9.876	9.873	9.871	9.875	9.878	9.880	9.872
R-180	36	9.870	9.884	9.877	9.873	9.868	9.867	9.868	o.876	o.874	o.865	o.863
R-181	37	9.872	9.873	9.872	9.877	9.876	9.876	9.874	9.877	9.876	9.885	9.887
R-188	39	9.868	9.872	9.874	9.879	9.875	9.869	9.879	9.889	9.885	9.873	9.862
R-189	40	9.878	9.882	9.873	9.877	9.881	9.886	9.884	9.879	9.884	9.877	9.872
R-191	41	9.875	9.881	9.879	9.880	9.873	9.875	9.879	9.880	9.874	9.871	9.867
R-192	42	9.885	9.885	9.878	9.878	9.875	9.875	9.872	9.878	9.883	9.879	9.882
R-193	43	9.869	9.882	9.885	9.885	9.875	9.871	9.872	9.880	9.880	9.877	9.867
R-194	44	9.879	9.882	9.881	9.884	9.874	9.873	9.871	9.875	9.882	9.883	9.876
R-196	45	9.873	9.882	9.872	9.874	9.875	9.879	9.877	9.879	9.876	9.860	9.855
R-197	46	9.875	9.882	9.881	9.881	9.875	9.875	9.877	9.886	9.882	9.871	9.865
R-198	47	9.877	9.881	9.874	9.879	9.880	9.887	9.888	9.880	9.887	9.875	9.870
R-201	48	9.886	9.884	9.885	9.891	9.882	9.887	9.889	9.890	9.892	9.883	9.875
Mean		9.875	9.880	9.877	9.880	9.875	9.876	9.877	9.880	9.881	9.875	9.870
Std. Dev.		.0053	.0039	.0043	.0046	.0031	.0064	.0068	.0048	.0051	.0070	.0086

Mean Standard Deviation: .0054 in.
Specified Dimension: 9.875 in.

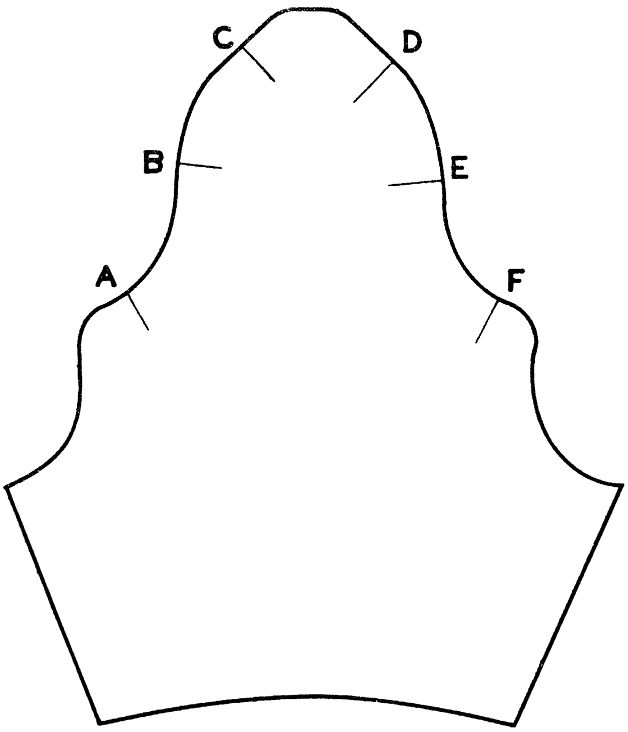
TABLE IV

PRECISION-CAST DRIVE SPROCKET, NO. 8671597

SPROCKET TOOTH-TIP RADIUS

Heat No.	Cast-ing No.	Tooth Numbers										
		1	2	3	4	5	6	7	8	9	10	11
R-179	35	13.856	13.856	13.855	13.856	13.855	13.848	13.853	13.857	13.858	13.862	13.857
R-180	36	13.847	13.856	13.863	13.861	13.851	13.843	13.853	13.852	13.854	13.853	13.844
R-181	37	13.853	13.857	13.858	13.858	13.858	13.856	13.861	13.863	13.864	13.861	13.850
R-188	39	13.849	13.853	13.858	13.861	13.861	13.845	13.861	13.867	13.868	13.866	13.849
R-189	40	13.856	13.864	13.862	13.866	13.864	13.862	13.869	13.865	13.870	13.867	13.855
R-191	41	13.858	13.862	13.865	13.866	13.859	13.854	13.857	13.860	13.857	13.860	13.856
R-192	42	13.869	13.864	13.867	13.866	13.858	13.861	13.854	13.861	13.865	13.868	13.868
R-193	43	13.849	13.863	13.866	1.874	13.864	13.857	13.862	13.866	13.869	13.864	13.853
R-194	44	13.864	13.864	13.866	13.869	13.862	13.850	13.857	13.857	13.862	13.867	13.864
R-196	45	13.849	13.852	13.862	13.857	13.855	13.854	13.865	13.862	13.862	13.864	13.842
R-197	46	13.858	13.867	13.871	13.870	13.863	13.856	13.862	13.871	13.870	13.865	13.857
R-198	47	13.857	13.861	13.863	13.864	13.863	13.864	13.876	13.864	13.874	13.869	13.857
R-201	48	13.864	13.868	13.870	13.870	13.867	13.862	13.871	13.879	13.881	13.871	13.863
Mean		13.856	13.861	13.864	13.864	13.860	13.856	13.862	13.863	13.866	13.864	13.855
Std. Dev.		.0065	.0050	.0045	.0053	.0043	.0064	.0068	.0065	.0071	.0045	.0072

Mean Standard Deviation: .0058 in.
Specified Dimension: 13.859 in.



Location of hardness survey on sprocket teeth.

TABLE V

ROCKWELL "C" HARDNESS SURVEY OF SPROCKET TOOTH
CAST AISI 4150—No. 195—AS-HARDENED

Specified - 55-60 R_c at 1/8 in.
Hardness - 50 R_c at 1/4 - 3/8 in.

Distance, 1/32 in.	Hardness					
	A	B	C	D	E	F
1	61.0	--	--	--	--	--
2	61.3	61.5	--	59.9	62.0	57.7
3	61.8	61.4	61.8	59.1	61.7	59.8
4	61.5	61.5	62.0	58.6	61.7	61.1
5	61.2	61.5	60.0	58.0	61.5	61.0
6	61.4	61.5	61.8	58.0	60.8	61.1
7	59.5	61.6	60.9	55.8	61.2	60.3
8	57.8	61.5	60.3	55.4	61.0	59.7
9	53.4	61.2	59.2	54.5	60.5	58.2
10	52.3	61.0	58.5	53.8	60.5	55.7
11	46.3	61.1	57.5	51.2	58.7	53.0
12	42.8	59.5	56.6	51.2	58.5	50.3
13	21.0	58.5	54.6	50.0	56.8	45.3
14	--	57.7	54.1	48.0	56.2	28.0
15	--	56.3	52.2	46.1	53.0	--
16	--	55.0	51.5	43.8	52.8	--
17	--	52.3	50.0	41.6	50.6	--
18	--	51.4	49.6	38.2	50.2	--
19	--	49.5	46.9	28.0	46.2	--
20	--	48.1	46.8	25.5	46.8	--

TABLE VI

SUMMARY OF SPROCKET TEST RESULTS

Place	Mileage	Average Maximum Wear of Cast Sprocket (in. per 1000 miles)	Average Maximum Wear of Fabricated Sprocket (in. per 1000 miles)
General Motors Military*			
Proving Ground Milford, Michigan	2416**	0.16	0.37
Aberdeen Proving Ground, Maryland	2359***	0.085	0.106
Fort Churchill* Ontario, Canada	1001	0.016	0.023
Yuma Test Station* Yuma, Arizona		under test	

* Thickness of cast sprockets, 1.675 in.; of fabricated, 1.375 in. in this test as only the thinner parts were available at the time. In other tests, all parts were 1.675 in. thick.

** Only the cast sprockets lasted this distance. Another pair of fabricated sprockets was worn out in the first 1239 miles of the test.

*** Cast sprockets applied after 514 miles. This is corrected for by using wear per 1000 miles in above calculations. Wear is approximately linear/mile.

TABLE VII

COMPARISON OF CAST AND FABRICATED DRIVE SPROCKET, NO. 8671597

Material	Fabricated Sprocket AISI 1345	Cast Sprocket AISI 4150
Weight of Stock, lb	363	195
Weight of Finished Sprocket, lb	94	94
Scrap Material, lb	260	101

TABLE VIII

PRECISION-CAST FINAL DRIVE GEAR, NO. 7364141

HEAT AND CASTING SUMMARY

Heat No.	Casting No.	Date	Mold Tilt, deg	Speed of Pour, sec/lb	Type of Risers, in. diam	Disposition
R-333	1	10-28-57	2	1.75	None	Scrap, mold did not fill
R-335	2	10-30-57	2	1.75	None	Scrap, mold did not fill
R-338	3	11-4-57	2	1.75	1-2	Scrap, partial runback
R-339	4	11-5-57	2	1.75	1-2	Scrap, partial runback
R-341	5	11-7-57	2	1.75	1-2	Scrap, partial runback
R-348	6	11-19-57	2	1.75	3-2-1/2	Scrap, shrinkage between risers
R-350	7	11-21-57	2	1.75	3-2-1/2	Scrap, shrinkage between risers
R-350	8	12-9-57	3-1/2	1.75	3-2-1/2	Wheel steel analysis, visually sound
R-350	9	12-17-57	3-1/2	1.75	3-2-1/2	Wheel steel analysis, visually sound
R-363	10	12-20-57	2	1.75	3-2-1/2	Scrap, poor surface
R-367	11	12-26-57	2	1.75	3-2-1/2	Scrap, x-rayed, slight shrinkage
R-367	12	1-11-58	3-1/2	1.75	3-2-1/2	Wheel steel analysis, experimental machining
R-408	13	2-11-58				Mechanical failure, heat-pigged
R-410	14	2-13-58	3-1/2	1.2	3-2-1/2	Sectioned, visually sound
R-414	15	2-18-58	3-1/2	1.2	3-2-1/2	Scrap, x-rayed, slight shrinkage
R-417	Blank No. 1	2-25-58	3-1/2	1.2	4-2-1/2	Scrap, x-rayed, moderate shrinkage
R-429	Blank No. 2	3-13-58	3-1/2	2.0	4-4	Sectioned, moderate shrinkage
R-430	16	3-17-58	3-1/2	2.0	6-2-1/2	Sectioned, visually sound
R-432	17	3-19-58	3-1/2	2.0	6-2-1/2	Scrap, off analysis
R-434	18	3-21-58	3-1/2	1.75	6-2-1/2	Scrap, off analysis
R-435	19	3-21-58	3-1/2	2.0	6-2-1/2	Scrap, off analysis
R-436	20	3-24-58	3-1/2	2.0	6-2-1/2	Scrap, off analysis
R-437	21	3-24-58	3-1/2	2.0	6-2-1/2	Scrap, off analysis
R-438		3-25-58				Mechanical failure, heat-pigged
R-440	22	3-27-58	3-1/2	2.0	6-2-1/2	Scrap, off analysis
R-444	23	3-31-58	3-1/2	2.0	6-2-1/2	SAE 1062, reserve stock, to Caterpillar

TABLE VIII (Continued)

Heat No.	Casting No.	Date	Mold Tilt, deg	Speed of Pour, sec/lb	Type of Risers, in. diam	Disposition
R-446	24	4-1-58	3-1/2	2.0	6-2-1/2	Scrapped, runback
R-450	25	4-7-58	3-1/2	2.0	6-2-1/2	Scrapped, wrinkles on teeth
R-452	26	4-8-58	3-1/2	2.0	6-2-1/2	Scrapped, runback
R-452	27	4-8-58	3-1/2	2.0	6-2-1/2	Scrapped, wrinkles on teeth
R-456	28	4-10-58	3-1/2	2.0	6-2-1/2	Wrinkle, 1 tooth
R-456	29	4-10-58	3-1/2	2.0	6-2-1/2	SAE 1062, reserve stock, to Caterpillar
R-461	30	4-15-58	3-1/2	2.0	6-2-1/2	SAE 1062, stock, to Caterpillar
R-461	31	4-15-58	3-1/2	2.0	6-2-1/2	SAE 1062, stock, to Caterpillar
R-463	32	4-16-58	3-1/2	2.0	6-2-1/2	SAE 1062, stock, to Caterpillar
R-463	33*	4-16-58	3-1/2	2.0	6-2-1/2	SAE 1062, reserve stock, to Caterpillar
R-467	34	4-21-58	3-1/2	2.0	6-2-1/2	Scrapped, bad teeth
R-467	35	4-21-58	3-1/2	2.0	6-2-1/2	Scrapped, large inclusion in bore
R-481	36	4-29-58	3-1/2	2.0	6-2-1/2	Scrapped, wrinkles on teeth
R-481	37	4-29-58	3-1/2	2.0	6-2-1/2	SAE 1062, reserve stock, hold
R-483	38	4-30-58	3-1/2	2.0	6-2-1/2	SAE 1062, stock, to Caterpillar
R-483	39	4-30-58	3-1/2	2.0	6-2-1/2	SAE 1062, stock, to Caterpillar
R-486	40*	5-5-58	2	2.0	6-2-1/2	SAE 1062, stock, to Caterpillar
R-486	41	5-5-58	2	2.0	6-2-1/2	Scrapped, bad wrinkle one tooth
R-487	42	5-6-58	2	1.75	6-2-1/2	SAE 1062, stock, to Caterpillar
R-487	43	5-6-58	2	1.75	6-2-1/2	SAE 1062, stock, to Caterpillar
R-489	44	5-12-58	2	1.75	6-2-1/2	Scrapped, bad wrinkle one tooth
R-489	45	5-12-58	2	1.75	6-2-1/2	SAE 1062, stock, to Caterpillar
R-490	46	5-13-58	2	1.75	6-2-1/2	SAE 1062, stock, to Caterpillar
R-490	47	5-13-58	2	1.75	6-2-1/2	SAE 1062, stock, to Caterpillar
R-491	48	5-14-58	2	1.75	6-2-1/2	Scrapped, bad wrinkles three teeth

TABLE VIII (Concluded)

Heat No.	Casting No.	Date	Mold Tilt, deg	Speed of Pour, sec/lb	Type of Risers, in. diam	Disposition
R-491	49	5-14-58	2	1.75	6-2-1/2	Scrapped, bad wrinkles one tooth
R-493	50	5-16-58	2	1.75	6-2-1/2	SAE 1062, stock, to Caterpillar
R-493	51*	5-16-58	2	1.75	6-2-1/2	SAE 1062, stock, to Caterpillar
R-496	52	5-25-58	2	1.75	6-2-1/2	Scrapped, bad wrinkles one tooth
R-496	53	5-25-58	2	1.75	6-2-1/2	Scrapped, bad wrinkles three teeth
R-497	54	5-26-58	2	1.75	6-2-1/2	SAE 1062, stock, to Caterpillar
R-497	55	5-26-58	2	1.75	6-2-1/2	Scrapped, wrinkles on teeth
R-498	56	5-27-58	2	1.75	6-2-1/2	Scrapped, gas hole in tooth
R-498	57	5-27-58	2	1.75	6-2-1/2	Scrapped, wrinkles on teeth
R-499	58	5-28-58	2	1.75	6-2-1/2	SAE 1062, stock, to Caterpillar
R-499	59	5-28-58	2	1.75	6-2-1/2	Scrapped, wrinkles one tooth
R-501	61	6-2-58	2	1.75	6-2-1/2	SAE 4817, stock, to Brad Foote
R-527	60	7-7-58	2	2.0	6-2-1/2	SAE 4817, gas holes, machined for test
R-527	62**	7-7-58	2	2.0	6-2-1/2	SAE 4817, stock, to Brad Foote
R-528	63	7-7-58	2	2.0	6-2-1/2	SAE 4817, stock, to Brad Foote
R-528	64	7-7-58	2	2.0	6-2-1/2	SAE 4817, stock, to Brad Foote
R-529	65	7-9-58	2	2.0	6-2-1/2	SAE 4817, stock, to Brad Foote
R-529	66**	7-9-58	2	2.0	6-2-1/2	SAE 4817, stock, to Brad Foote
R-530	67	7-9-58	2	2.0	6-2-1/2	SAE 4817, stock, to Brad Foote
R-530	68	7-9-58	2	2.0	6-2-1/2	SAE 4817, stock, to Brad Foote
R-531	69**	7-10-58	2	2.0	6-2-1/2	SAE 4817, stock, to Brad Foote
R-531	70**	7-10-58	2	2.0	6-2-1/2	SAE 4817, stock, to Brad Foote

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*Radiographically sound.

**Scrapped after carburizing due to decrease in size.

TABLE IX

PRECISION-CAST FINAL DRIVE GEAR, NO. 7364141
CHEMICAL ANALYSIS - CASTINGS SUBMITTED FOR TEST

Heat	Casting	Chemical Analysis						
No.	No.	C	Mn	Si	P	S	Ni	Mo
R-444	23	.62	.98	.31	.010	.020		
R-456	29	.65	.90	.33	.010	.016		
R-461	30	.63	.98	.30	.012	.018		
R-461	31	.63	.98	.30	.012	.018		
R-463	32	.67	.91	.28	.011	.026		
R-463	33	.67	.91	.28	.011	.026		
R-483	38	.64	.96	.24	.012	.020		
R-483	39	.64	.96	.24	.012	.020		
R-486	40	.60	.95	.35	.011	.024		
R-487	42	.60	.93	.26	.007	.014		
R-487	43	.60	.93	.26	.007	.014		
R-489	45	.59	.90	.25	.008	.018		
R-490	46	.64	.91	.25	.013	.016		
R-490	47	.64	.91	.25	.013	.016		
R-493	50	.60	.91	.26	.009	.026		
R-493	51	.60	.91	.26	.009	.026		
R-497	54	.56	.90	.23	.014	.024		
R-499	58*	.58	.94	.29	.019	.022		
R-501	61	.21	.66	.28	.019	.018	3.47	.23
R-527	60	.15	.69	.28	.012	.014	3.44	.25
R-527	62	.15	.69	.28	.012	.014	3.44	.25
R-528	63	.18	.62	.24	.014	.012	3.46	.25
R-528	64	.18	.62	.24	.014	.012	3.46	.25
R-530	65	.16	.65	.27	.010	.012	3.50	.25
R-530	66	.16	.65	.27	.010	.012	3.50	.25
R-531	67	.22	.65	.26	.009	.016	3.53	.25
R-531	68	.22	.65	.26	.009	.016	3.53	.25
R-532	69	.20	.72	.26	.009	.012	3.51	.25
R-532	70	.20	.72	.26	.009	.012	3.51	.25

*Cast in larger mold. Pin diameter approximately .120 in. larger.

TABLE X

PRECISION-CAST FINAL DRIVE GEAR, NO. 7364141
SUMMARY OF PIN-DIAMETER DATA*
CASTINGS NOS. 17 THROUGH 54

Gear Number	Σ X	$\overline{X}$	Σ X^2	σ X	$\frac{\overline{X} - 19.730}{4}$
17	654.782	19.842	12,992.106	.005	.028
18	655.191	19.854	13,007.452	.007	.031
19	655.238	19.856	13,010.209	.007	.0270
20	654.704	19.839	12,990.440	.007	.0272
22	654.724	19.840	12,989.804	.004	.0275
23	654.310	19.825	12,973.382	.005	.0237
29	655.224	19.823	13,009.653	.007	.0232
30	654.903	19.843	12,996.908	.005	.0282
31	655.538	19.832	13,022.125	.007	.0280
32	654.991	19.846	13,000.402	.007	.0290
33	654.695	19.837	12,988.654	.006	.0267
34	654.419	19.829	12,977.705	.006	.0247
35	655.787	19.840	13,012.144	.007	.0275
38	655.287	19.825	13,012.153	.003	.0237
39	655.224	19.823	13,009.652	.008	.0232
40	654.875	19.843	12,995.796	.004	.0282
42	654.380	19.828	12,976.158	.005	.0245
43	654.138	19.820	12,966.562	.005	.0225
44	654.432	19.829	12,978.221	.007	.0247
45	654.723	19.838	12,989.765	.006	.0270
46	654.916	19.844	12,997.425	.007	.0285
47	654.981	19.846	13,000.242	.004	.0290
50	654.667	19.836	12,987.543	.006	.0265
51	654.671	19.837	12,987.701	.004	.0267
54	654.895	19.843	12,996.590	.004	.0282
Σ X		495.918		.143	.6644
$\overline{X}$		19.837		.006	.027
Σ X^2		9837.389			
σ X		.010			
Range		19.856 to 19.820			.0310 to .0225

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*Q-1 through Q-33 individual measurements.

TABLE XI

PRECISION-CAST FINAL DRIVE GEAR, NO. 7364141
SUMMARY OF PIN-DIAMETER DATA*
CASTINGS NOS. 58 THROUGH 70

Gear Number	ΣX	$\bar{X}$	ΣX^2	σX	$\frac{\bar{X} - 19.730}{4}$
58	657.878	19.934	13,115.258	.007	.0510
60	658.096	19.910	13,123.951	.006	.0450
61	658.648	19.927	13,145.976	.004	.0492
62	658.092	19.910	13,123.792	.007	.0450
63	658.720	19.929	13,148.851	.006	.0497
64	659.018	19.908	13,160.750	.005	.0445
65	658.802	19.931	13,152.125	.007	.0502
66	658.582	19.925	13,143.343	.007	.0487
67	658.891	19.934	13,155.678	.005	.0510
68	658.300	19.916	13,132.089	.006	.0465
69	659.151	19.912	13,166.064	.007	.0455
70	658.505	19.922	13,140.268	.004	.0480
ΣX		239.058		.071	.5743
$\bar{X}$		19.922		.006	.048
ΣX^2		4762.395			
σX		.010			
Range		19.934 to 19.910			.0450 to .0510

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*Q-1 through Q-33 individual measurements.

TABLE XII

PRECISION-CAST FINAL DRIVE GEAR, NO. 7364141
SUMMARY OF GEAR MEASUREMENT DATA
CASTINGS NOS. 17 THROUGH 70

	ΣX	$\bar{X}$	ΣX^2	σX
A-1	31.305	.869	27.226	.010
A-2	31.320	.870	27.252	.010
A-3	31.333	.870	27.266	.007
A-4	31.315	.870	27.244	.009
$\bar{X}$		.870		.009
J-1	202.422	5.621	1,138.189	.010
J-2	202.423	5.621	1,138.199	.008
$\bar{X}$		5.621		.009
L-1	720.827	19.477	14,043.160	.016
L-2	721.353	19.491	14,063.643	.025
$\bar{X}$		19.484		.020
P-1	120.275	3.250	390.977	.007
P-2	120.240	3.249	390.750	.008
P-3	120.288	3.250	391.062	.008
P-4	120.222	3.248	390.632	.006
$\bar{X}$		3.249		.007

A-1 through A-4 - Plate Thickness
J-1 and J-2 - Hub Diameter
L-1 and L-2 - Outside Diameter
P-1 through P-4 - Rim Thickness

TABLE XIII

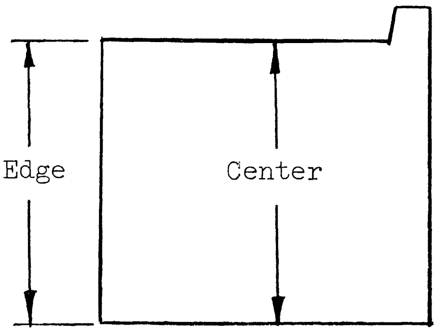
COMPARISON OF FORGED VERSUS CAST CRANKSHAFT
14-v - 1790 Engine

	Forged 1790 Crankshaft	Cast 1790 Crankshaft
Material	SAE 4340	SAE 4340
Weight of Stock, lb	418	315
Finished Weight, lb	250	232
Scrap Material, lb	168	83
Finished Cost	$500.00	$250.00

Estimated savings per crankshaft: $250.00
Estimated production, 1958: 900
Total estimated savings: $225,000.00

TABLE XIV

DIMENSIONAL VARIATIONS IN REAR FOLLOWER CASTINGS



Heat No. 676		Heat No. 682		Heat No. 671	
Center	Edge	Center	Edge	Center	Edge
2.605	2.572	2.578	2.560	2.615	2.590
2.588	2.576	2.571	2.557	2.611	2.598
2.576	2.567	2.591	2.578	2.610	2.594
		Differences			
0.033		0.018		0.025	
0.012		0.014		0.013	
0.009		0.013		0.016	
		Average Difference of Bulge			
0.018 or 0.007 in./in.		0.015 or 0.006 in./in.		0.018 or 0.007 in./in.	

TABLE XV

DIMENSIONAL VARIATION IN STEEL STEP CASTINGS, CONVENTION SHELL-MOLDING WITH GREEN SAND BACKING

Heat No.	Dimensions "A"	Dimensions "C"	Bulge in./in.
5	1.964	1.960	- .002
14	1.979	2.026	+ .023
15	2.047	2.083	+ .018
20	2.019	2.004	- .007
21	2.014	2.043	+ .015
25-C	1.959	1.964	+ .002
27-C	1.985	1.980	- .002

Range of Analysis

C	Mn	Si
.2-.3	.2-.4	.15-.5

TABLE XVI

DIMENSIONAL VARIATION IN GREY CAST IRON STEP CASTINGS

Heat No.	Dimensions "A"	Dimensions "C"	Bulge in./in.
691-1	1.964	1.969	0.002
691-3	1.982*	1.989	0.004
691-2	1.979*	1.988	0.003
A581	1.981	1.977	0.002
A582	1.984	1.985	0.000
A584	1.967	1.968	0.001
A585	1.965	1.965	0.000
A586	1.962	1.960	0.000

Analysis ... as charged

C	Si	Mn	S	P
3.60	2.20	.10	.05	.05

*Cast with green sand backing.

TABLE XVII

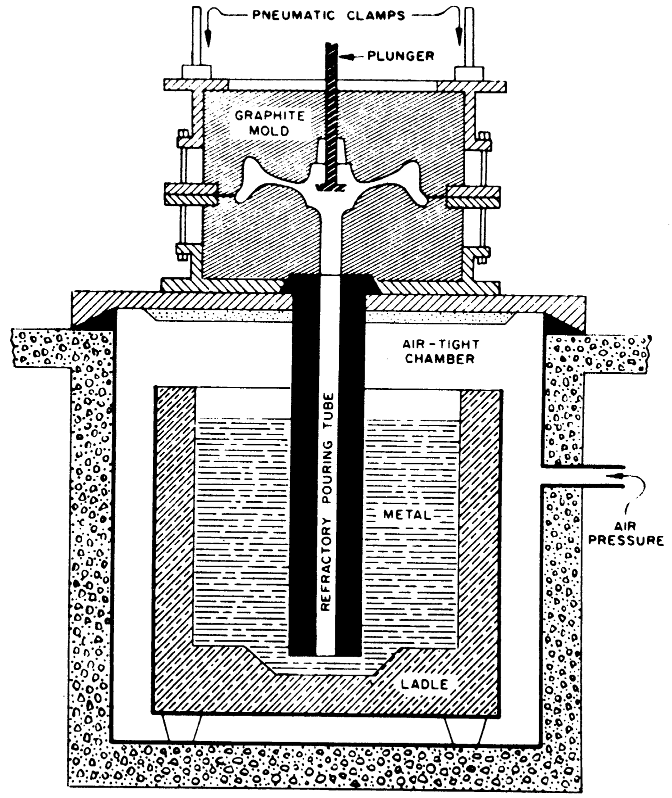
DIMENSIONAL VARIATION IN SHELL STEP MOLD CAST IN DUCTILE IRON

	Total Force on Mold, lb	Bulge in./in. (in 2-in. section)	Dimension "A" Edge of Step
	Static Backing		
Metal shot number			
A20-2	40	0.029	2.038
685-8	80	0.055	2.019
682	24	0.105	2.072
Sand, mold number			
662-1	--	0.017	2.012
A20-3	45	0.032	2.002
664-1	7	0.054	2.064
Sand + weight			
A20-4	45	0.015	1.989
685-7	44	0.055	2.012
A55-1	27	0.104	2.114
CO_2 process mold			
A28-3	--	0.033	2.021
A28-2	--	0.039	2.027
	Dynamic Backup - Spring Clamps		
Mold number			
A54-1	18	0.017	2.006
A55-2	60	0.017	1.992
A54-2	60	0.015	1.990
671-1	60	0.007	1.986
A54-3	60	0.007	1.998
683	90	0.006	1.979
A55-4	120	0.009	1.986
A54-4	120	0.002	1.968
673-1	120	0.005	1.995
676-3	150	0.006	1.974
A54-5	180	0.003	1.975
A55-5	180	0.006	1.976
680	180	0.001	1.996
A28-1	180	0.008	1.981
A20-1	180	0.002	1.984
A54-6	240	0.000	1.978
A55-6	240	0.000	1.960

TABLE XVIII

SUMMARY OF EXPERIMENTAL DATA
IRON-SILICA INTERFACE REACTION

Specimen No.	Gas Mixture		Temperature, °C	Time, min	Phases Present
	% CO_2	% CO			
1	50	50	1225	3	Metal, silica, fayalite
2	50	50	1225	5	
3	50	50	1225	15	
4	50	50	1225	60	
5	50	50	1525	3	Metal, silica, fayalite
6	50	50	1525	5	
7	50	50	1525	15	
8	50	50	1525	60	
9	50	50	1565	60	Silica, fayalite, magnetite
10	10	90	1225	60	Silica, metal
11	10	90	1525	3	Metal, silica, fayalite
12	10	90	1525	5	
13	10	90	1525	15	
14	10	90	1525	60	
15	2.7	97.3	1525	60	Metal, silica
16	2.7	97.3	1565	60	Metal, silica



Showing arrangement of graphite mold, ladle, and tube during pressure-pouring operation. Mold risers not shown. Pouring speed is closely regulated to prevent mold erosion. Operation is pushbutton controlled

Fig. 1. Production of railroad car wheels in pressure-poured graphite mold.

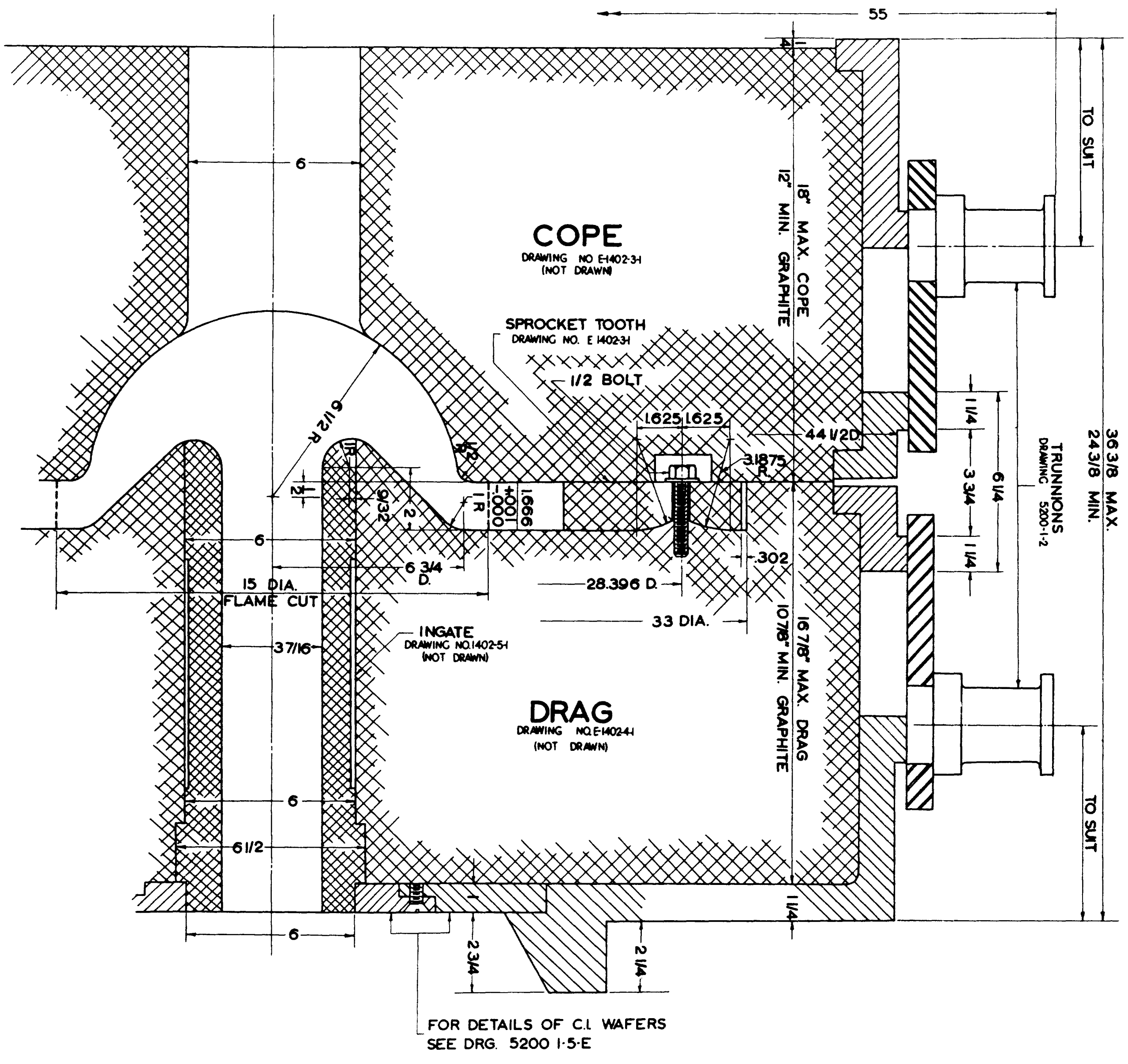


Fig. 2. Permanent mold design for precision-cast drive sprocket, Part No. 8671597.

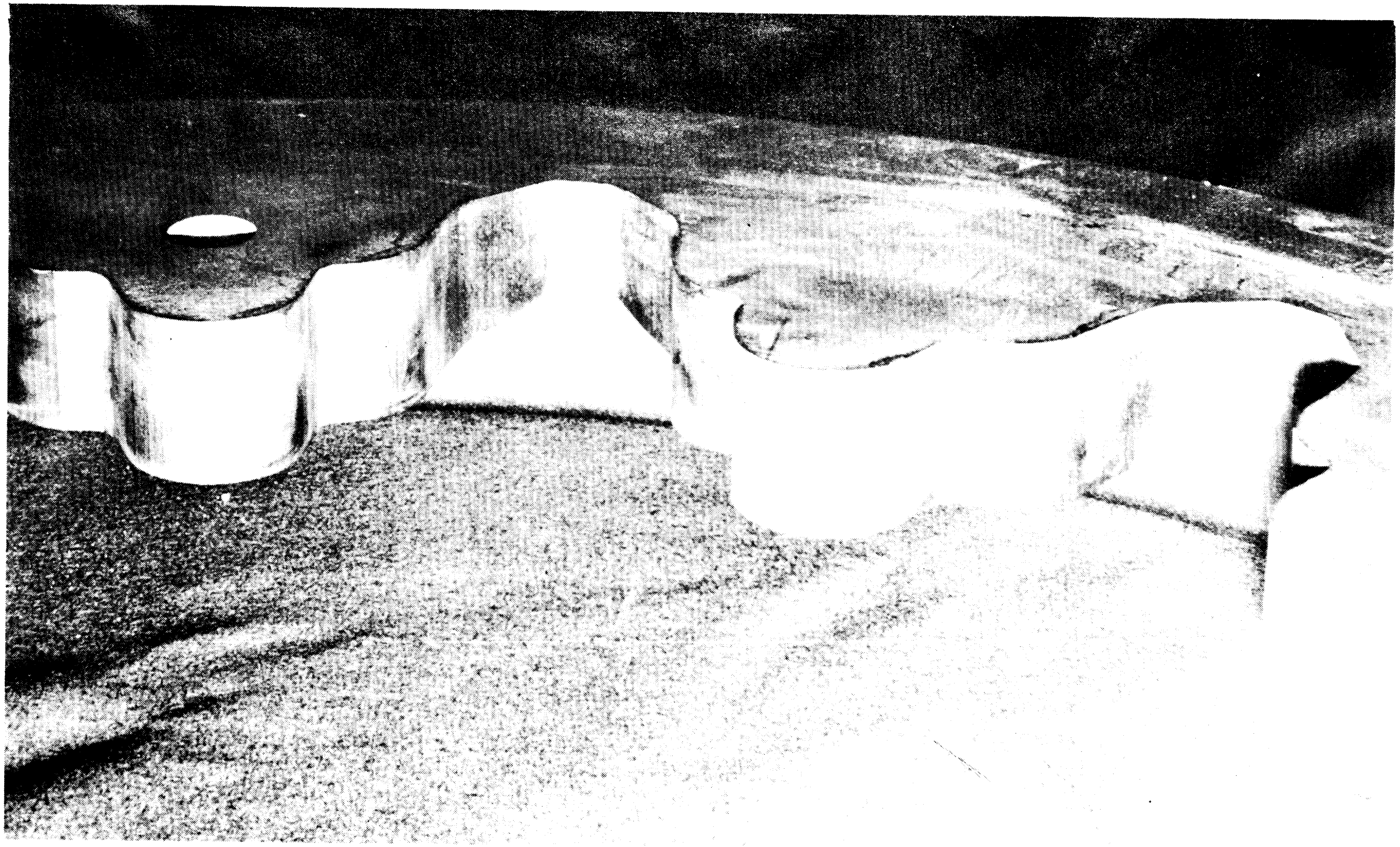


Fig. 3. Surface of gray iron insert for sprocket mold after producing 26 castings.

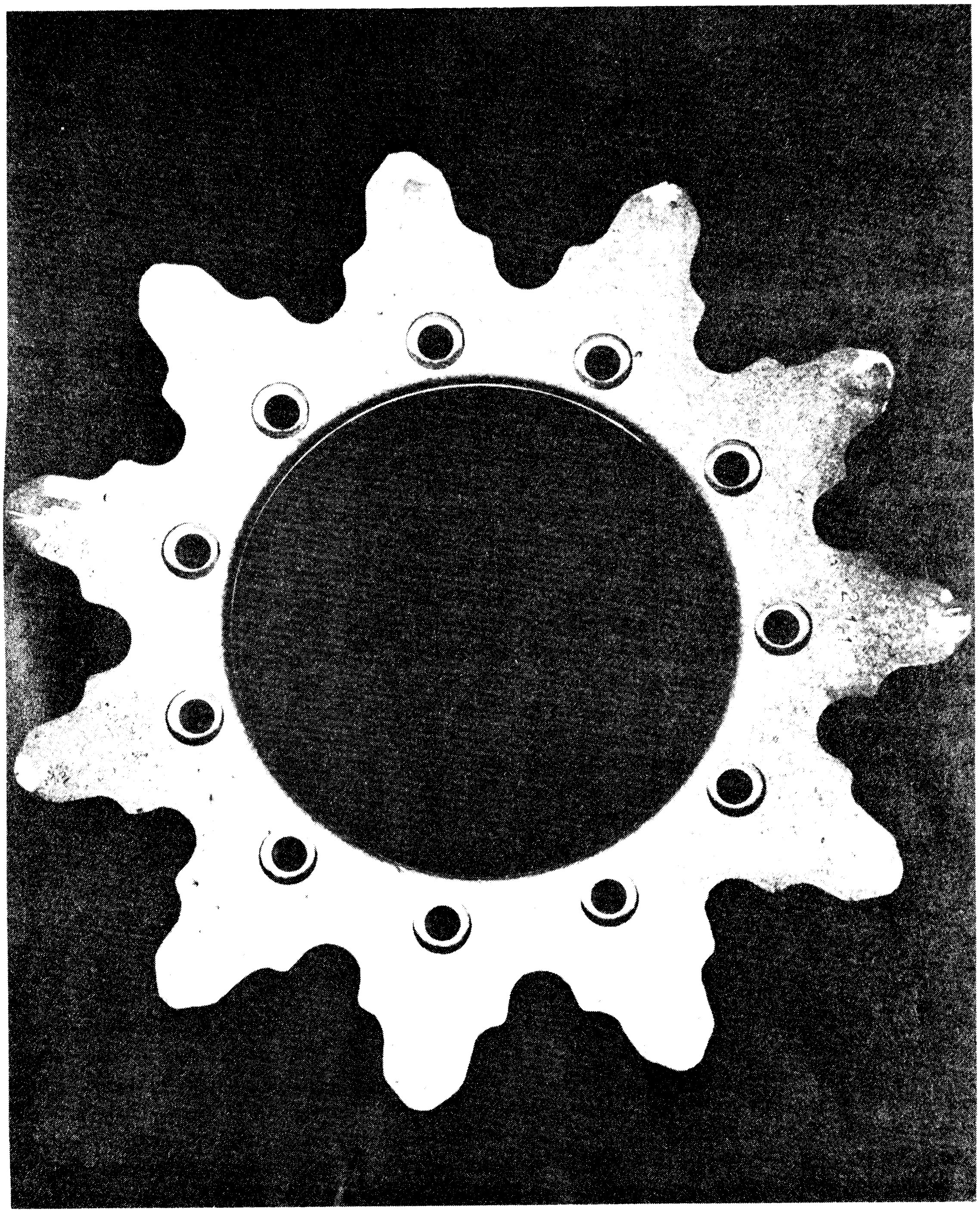
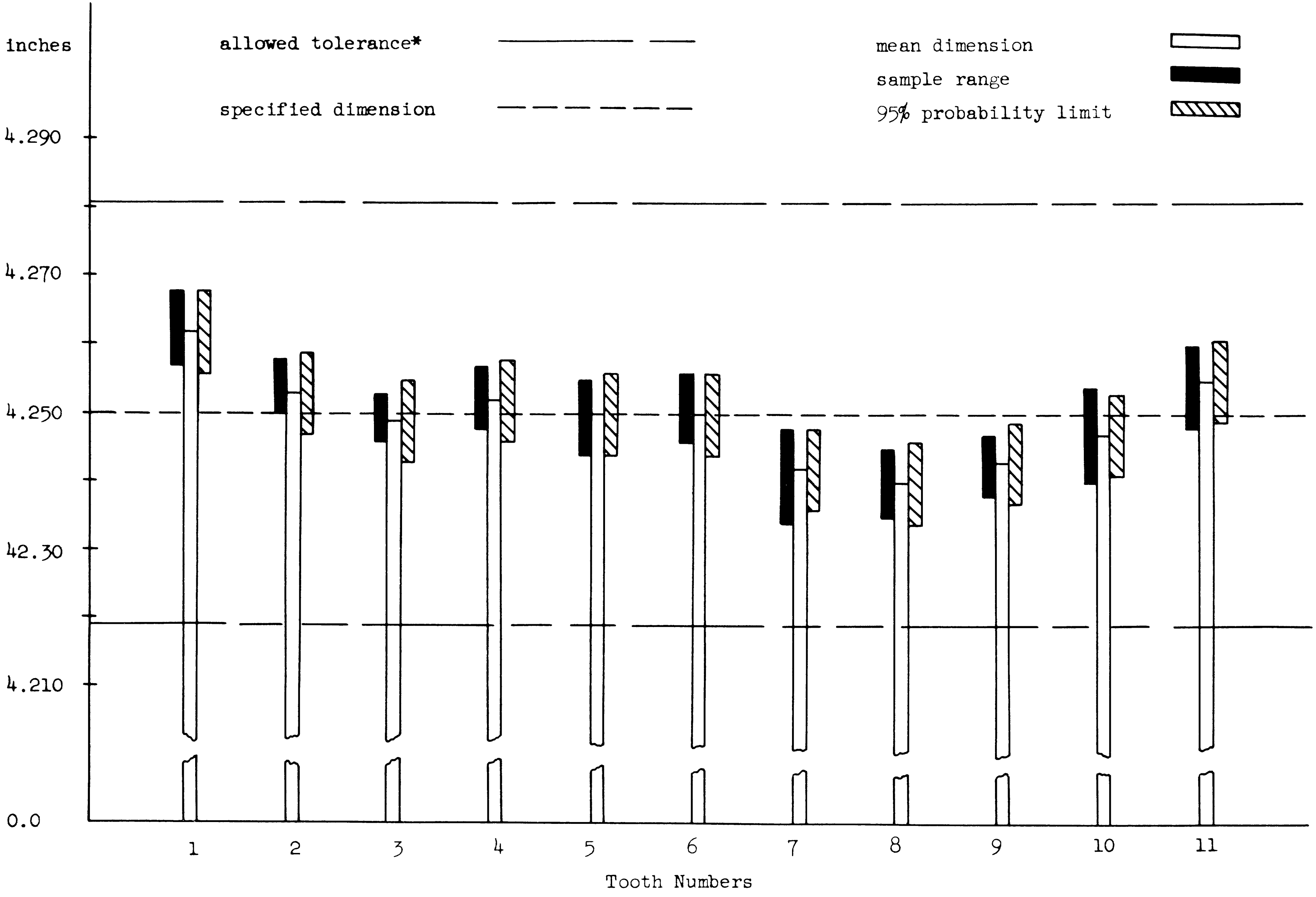
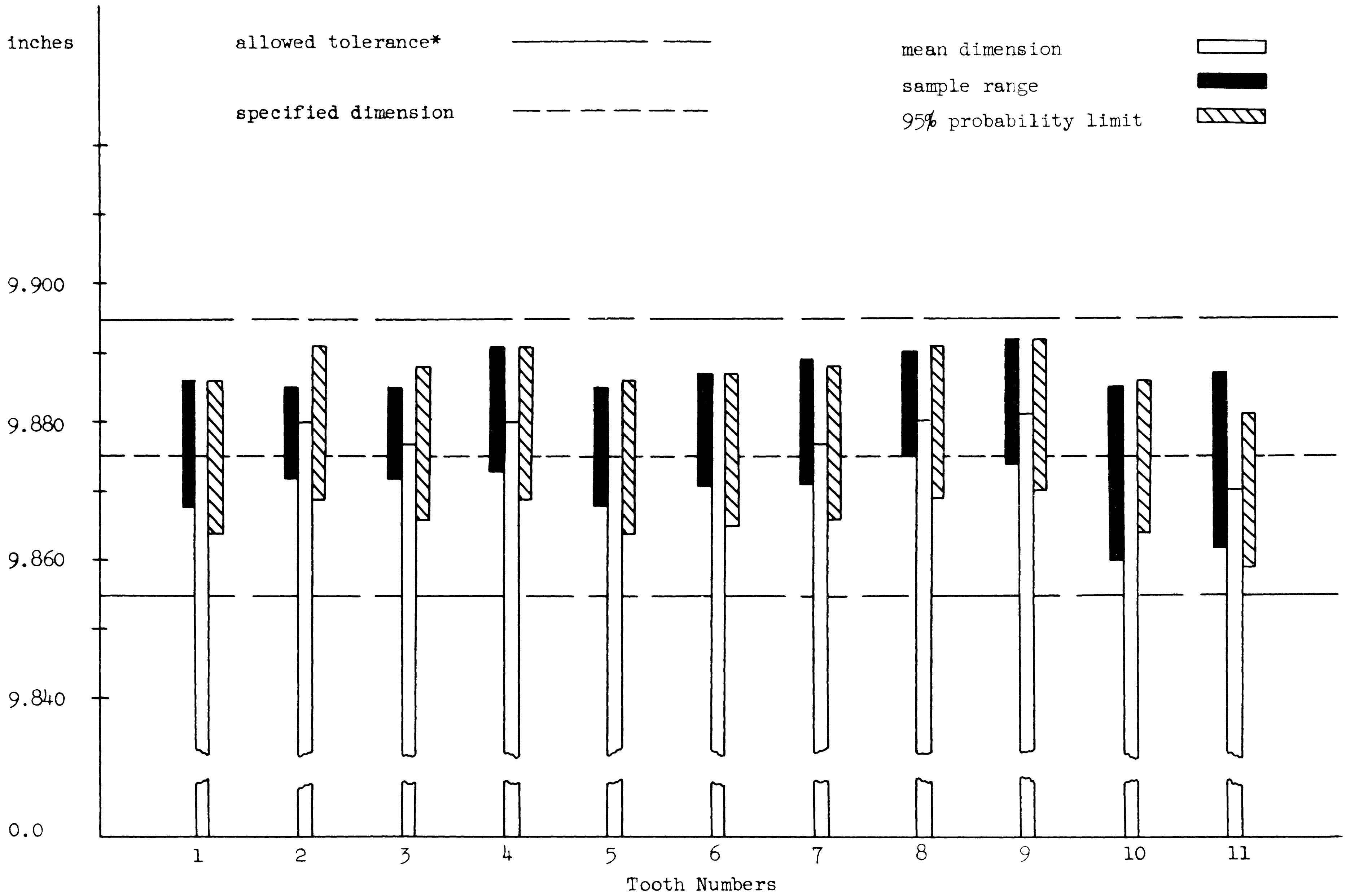


Fig. 4. Drive sprocket cast in armor analysis.



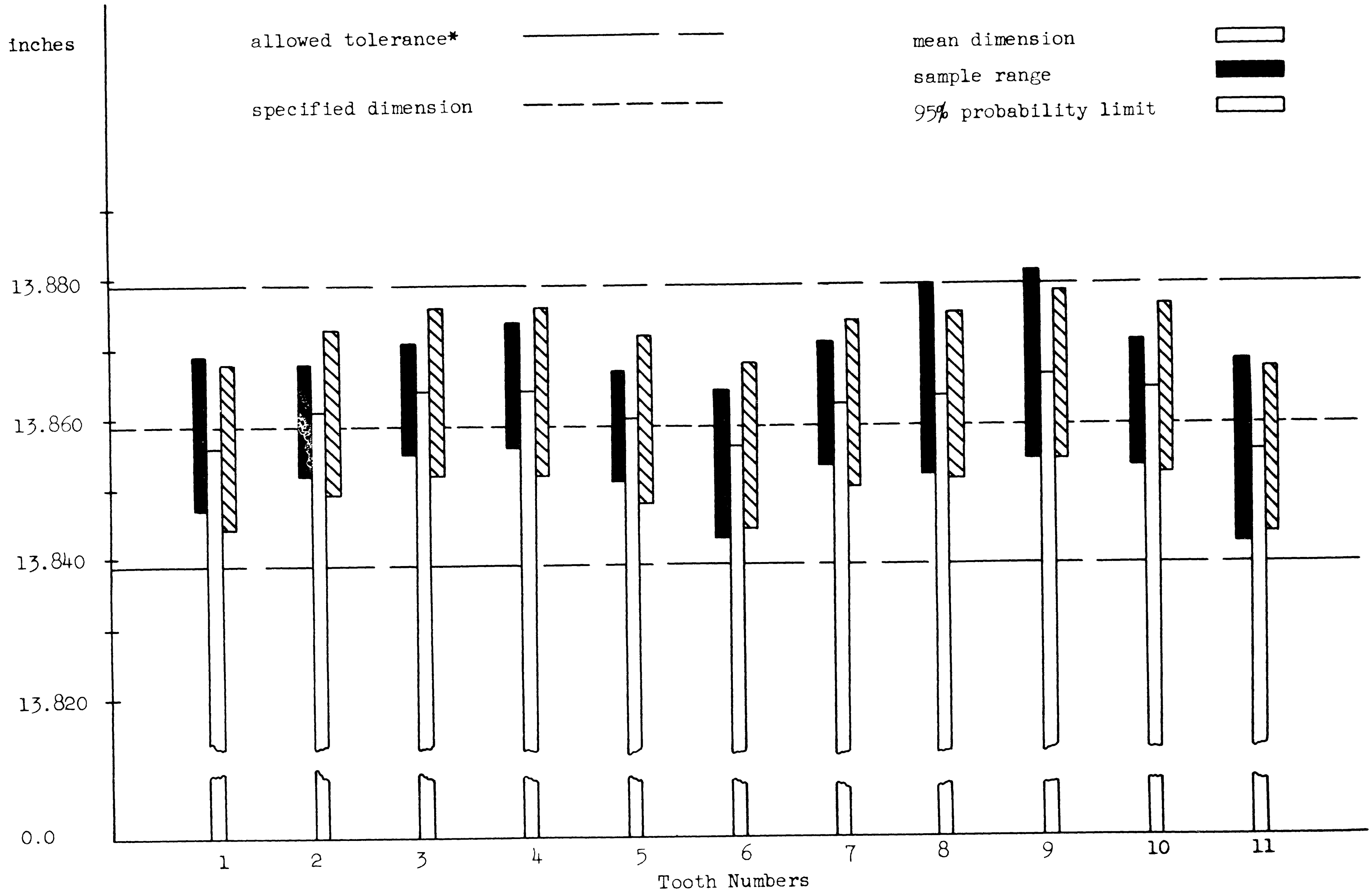
*Specified tolerance equal to this dimension.

Fig. 5. Tooth base width showing sample range and 95% probability limits, precision-cast drive sprocket, Part No. 8671597.



*Allowed tolerance modified to be equi-distant from specified dimension.

Fig. 6. Tooth root radii showing sample range and 95% probability limits, precision-cast drive sprocket, Part No. 8671597.



*Allowed tolerance modified to be equi-distant from specified dimension.

Fig. 7. Tooth tip radii showing sample range and 95% probability limits, precision-cast drive sprocket, Part No. 8671597.

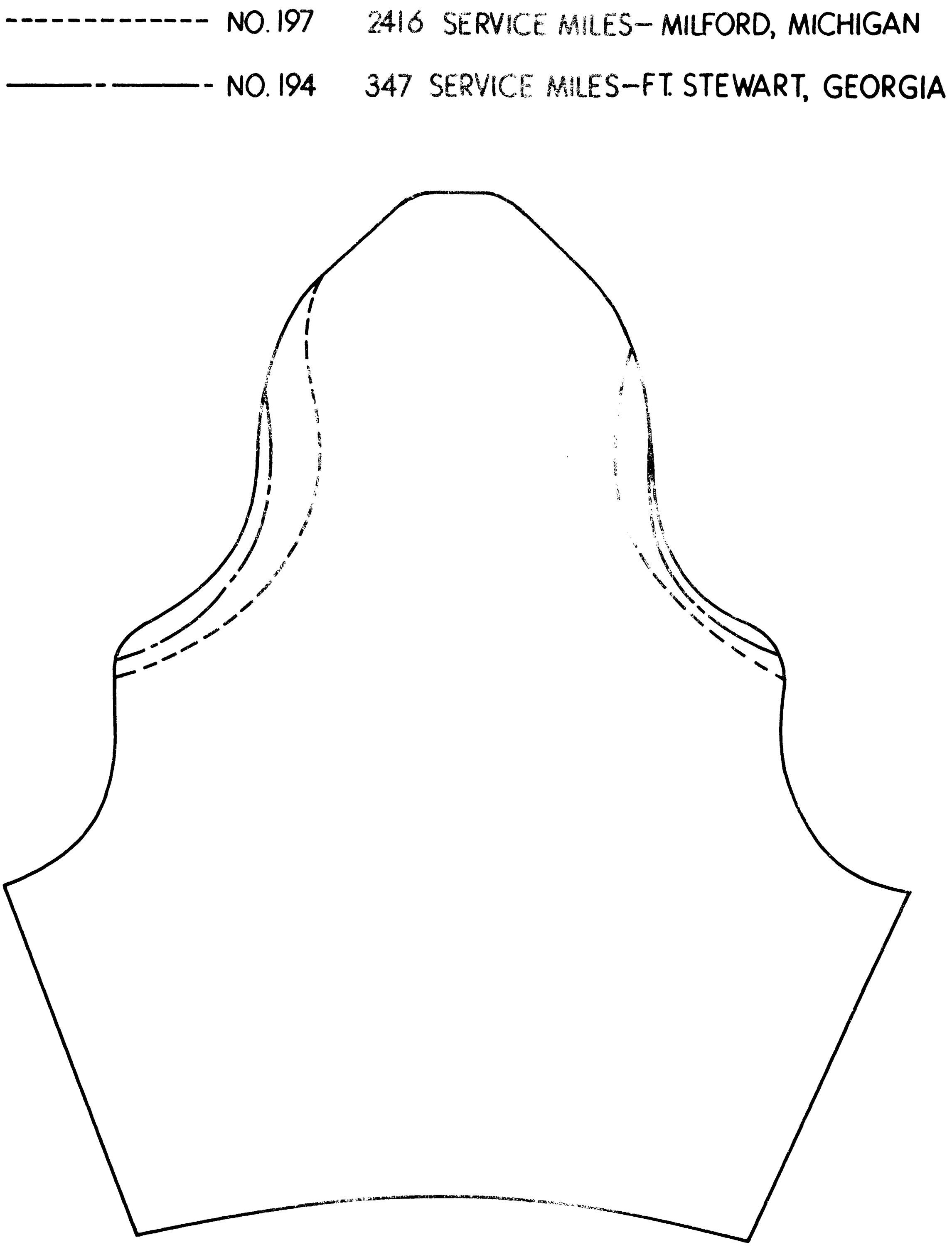
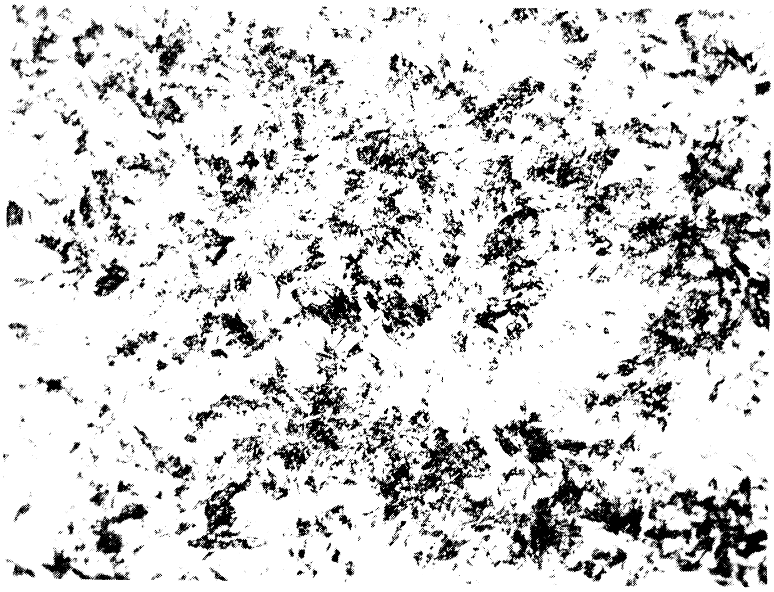
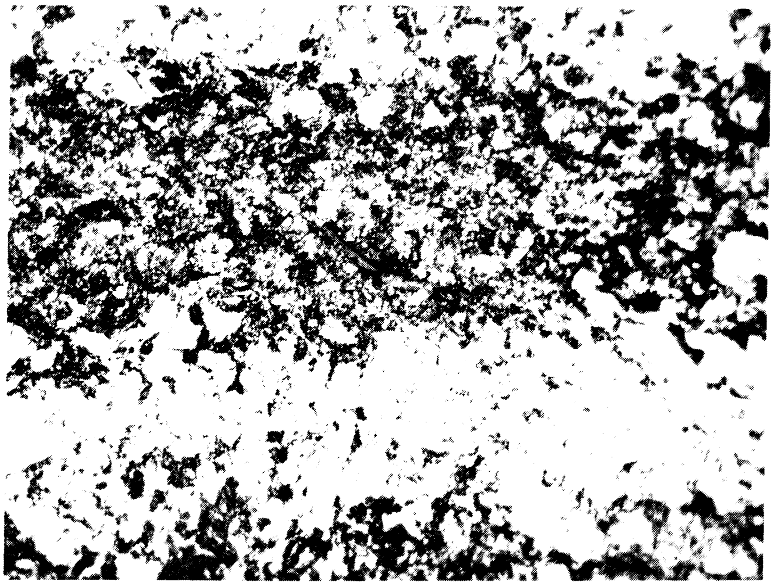


Fig. 8. Comparative wear patterns, precision-cast drive sprockets, Part No. 8671597.



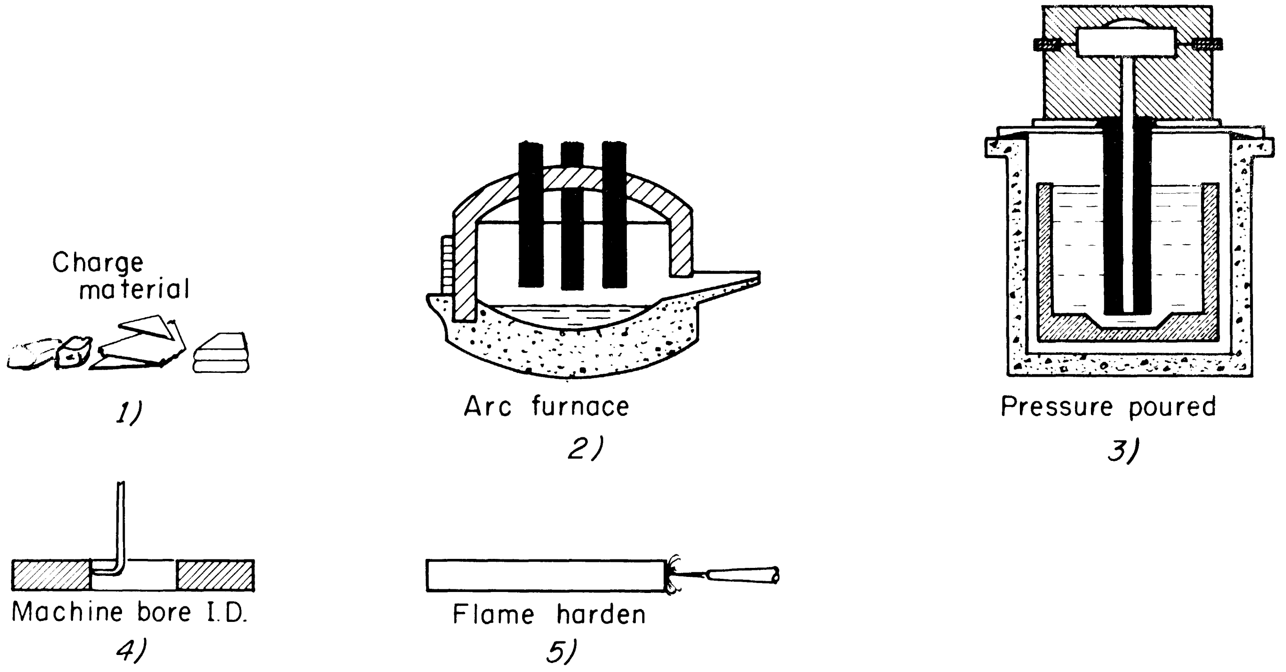
Transition Zone 500X 2% Nital

Fig. 9a. Cast AISI 4150 sprocket, No. 197.

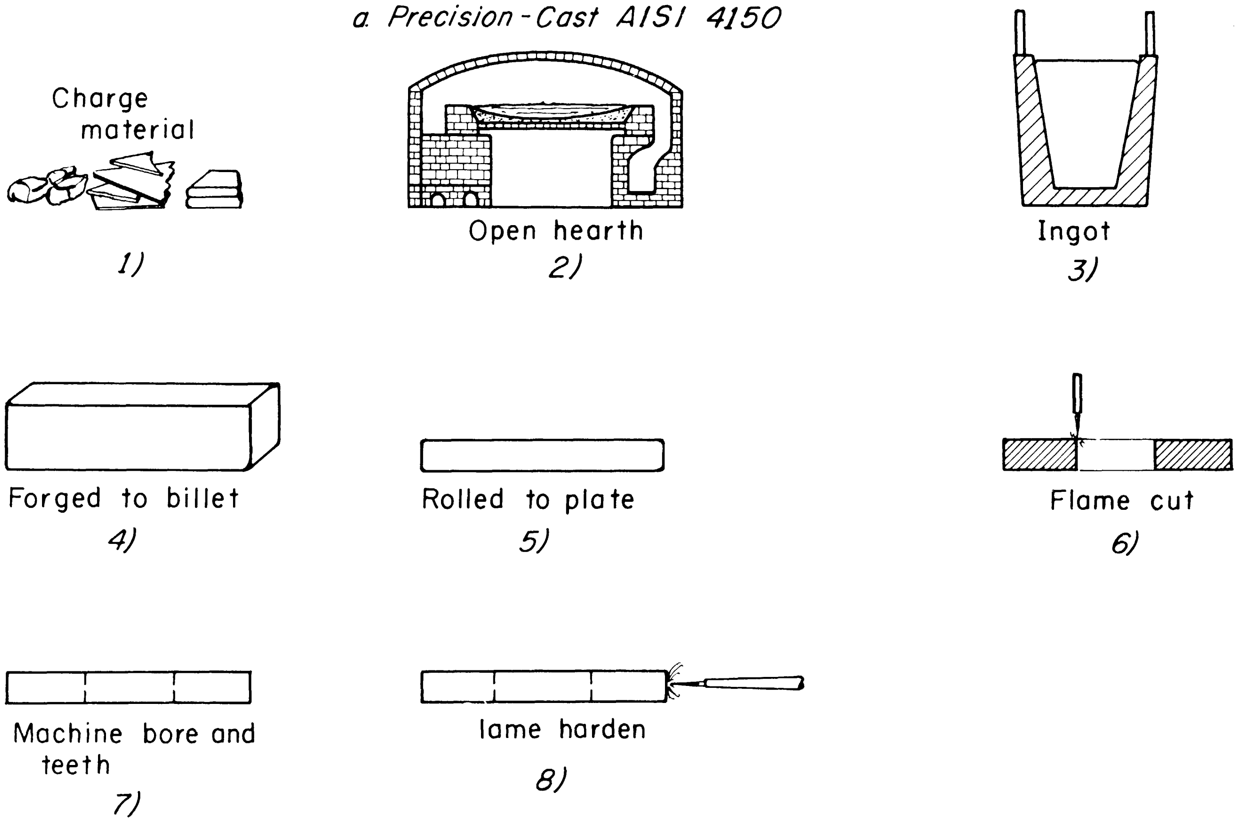


Transition Zone 500X 2% Nital

Fig. 9b. Fabricated AISI 1345 sprocket A.



a. *Precision-Cast AISI 4150*



b. *Fabricated AISI 1345*

Fig. 10. Manufacturing operations for production of cast and fabricated drive sprockets, Part No. 8671597.

Fig. 11a. Shell-cast front follower, Part No. 7360356. Reduced to 1/8 size.

Fig. 11b. Shell-cast rear follower, Part No. 7359510. Reduced to 1/8 size.

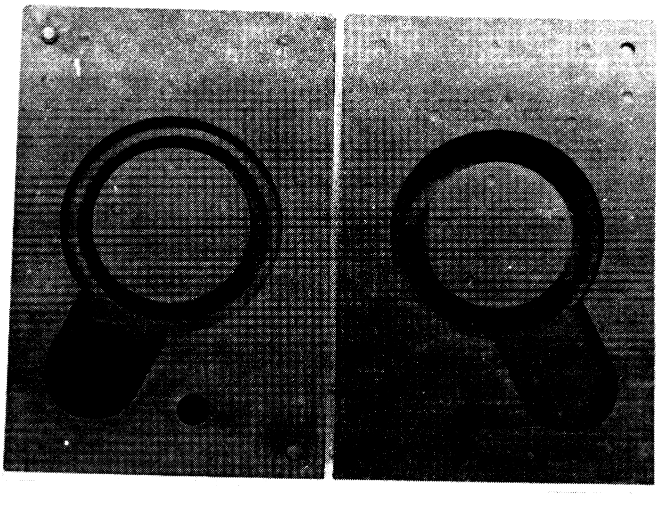


Fig. 12a. Shell mold for front follower, Part No. 7360356.

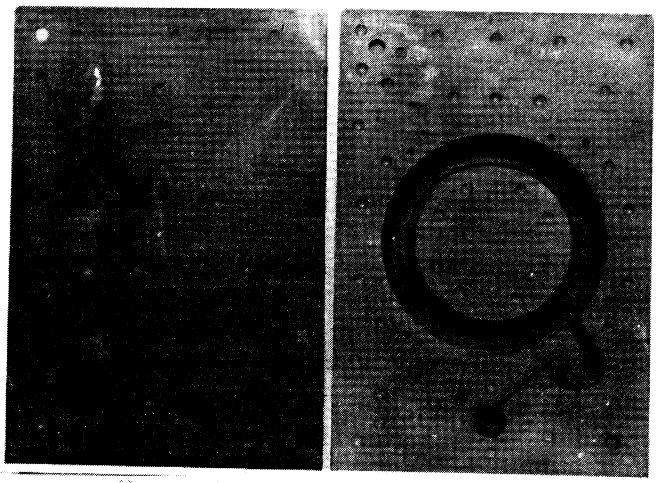


Fig. 12b. Shell-mold for rear follower, Part No. 7359510.

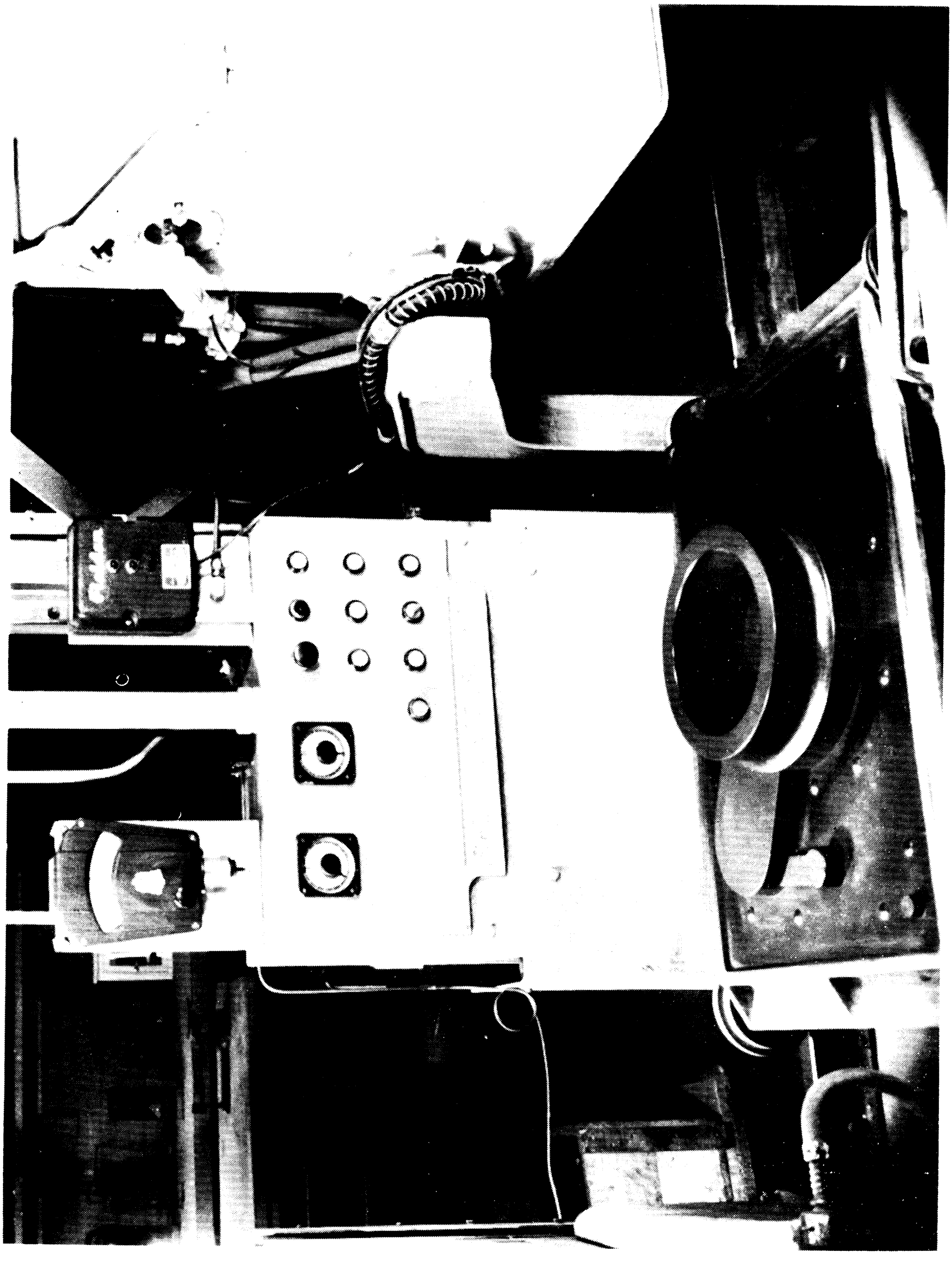
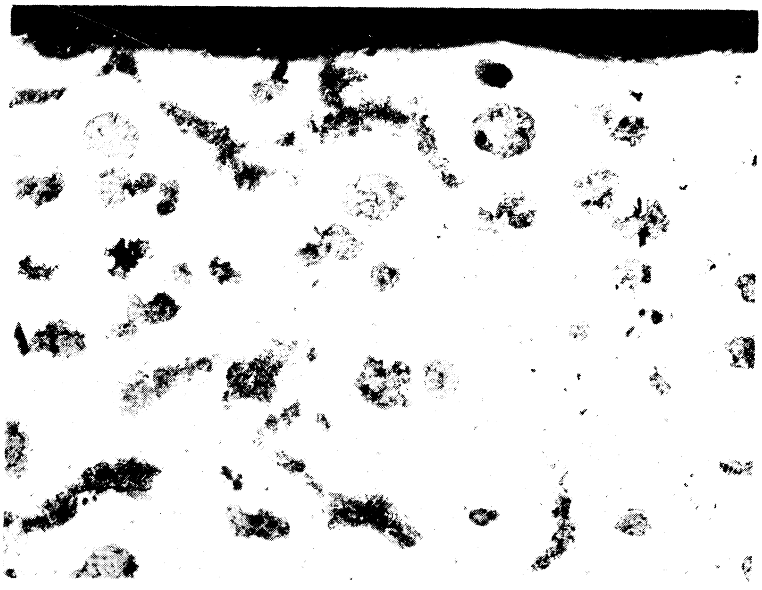
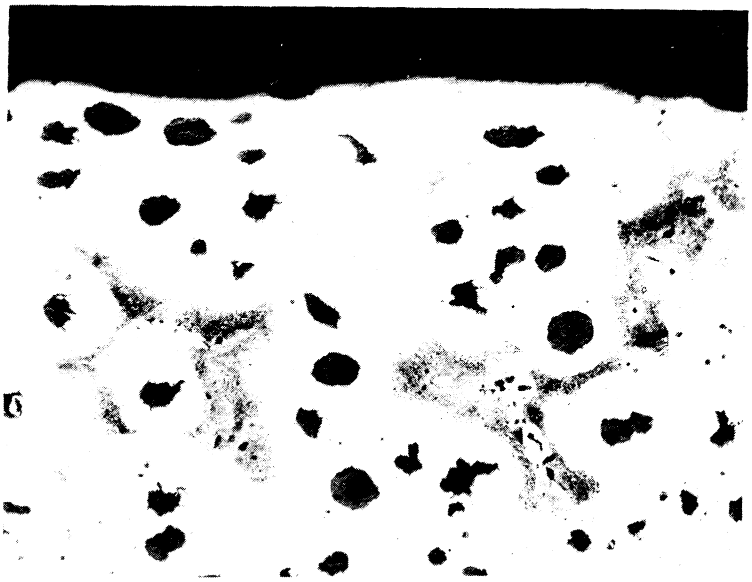


Fig. 13. Shell Process Company molding machine with front follower pattern, Part No. 7360356.



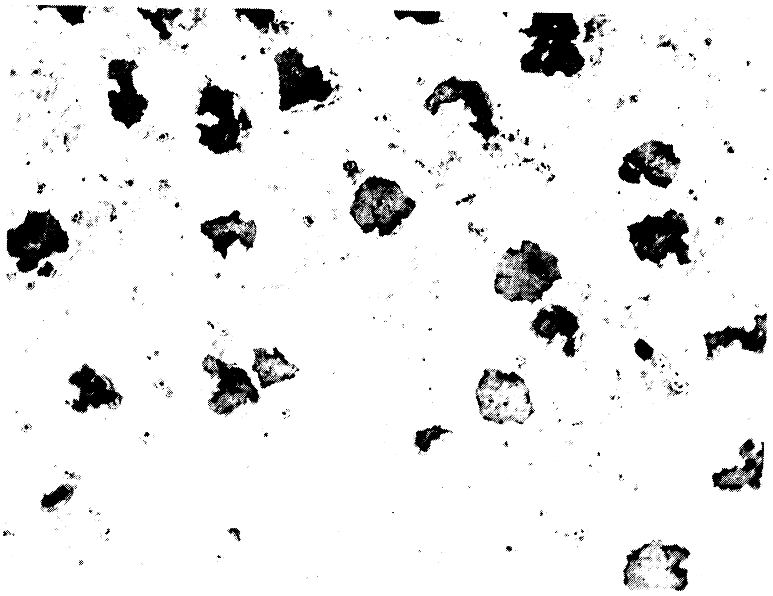
Scored Edge 100X 2% Nital

Fig. 14a. As-cast ductile iron front follower, Part No. 7360356.



Scored Edge 100X 2% Nital

Fig. 14b. As-cast ductile iron rear follower, Part No. 7359510.



Control Specimen 100X 2% Nital

Fig. 15. Normalized ductile iron for replacement follower castings.

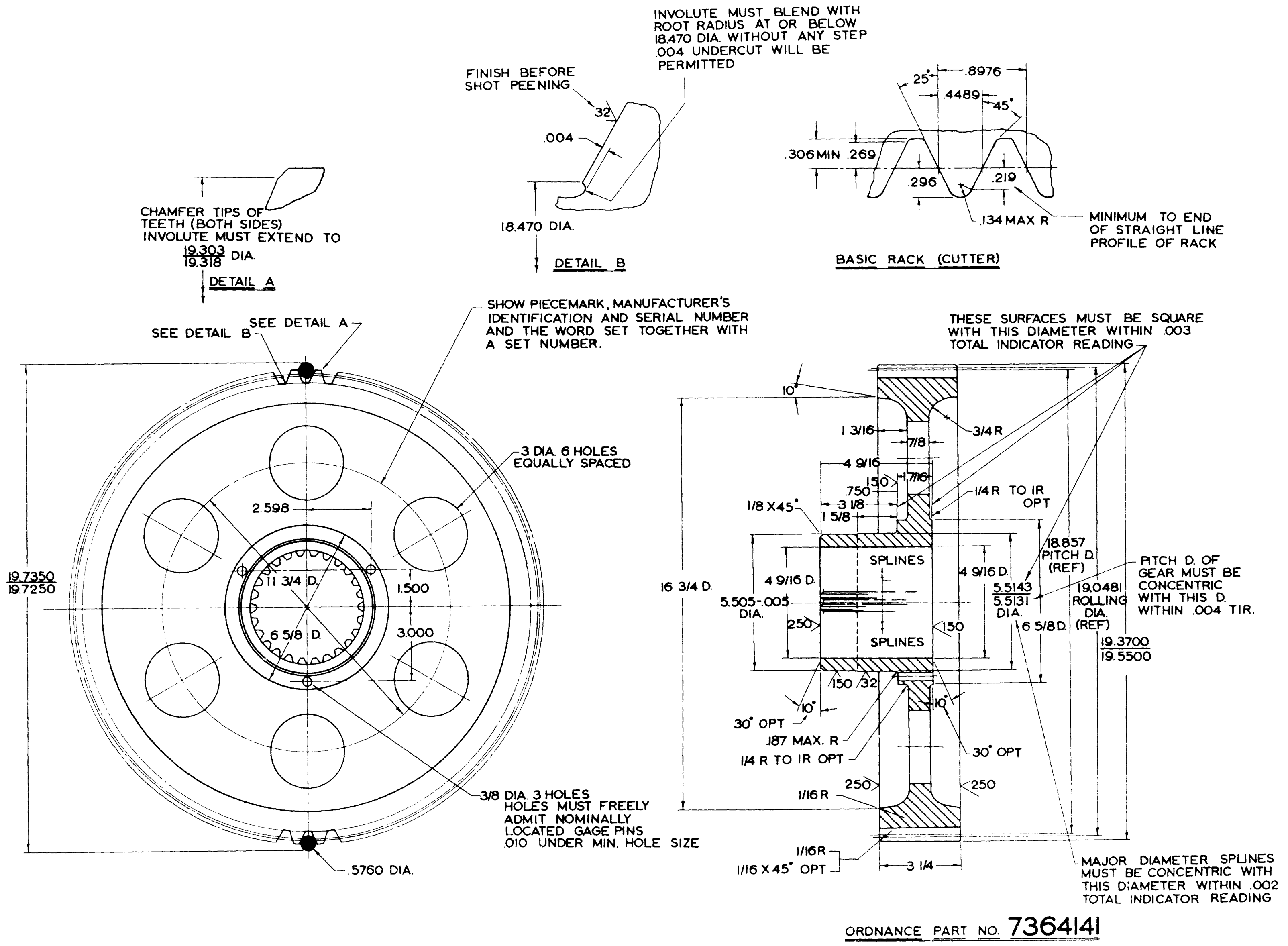


Fig. 16. Final drive gear, Part No. 7364141.

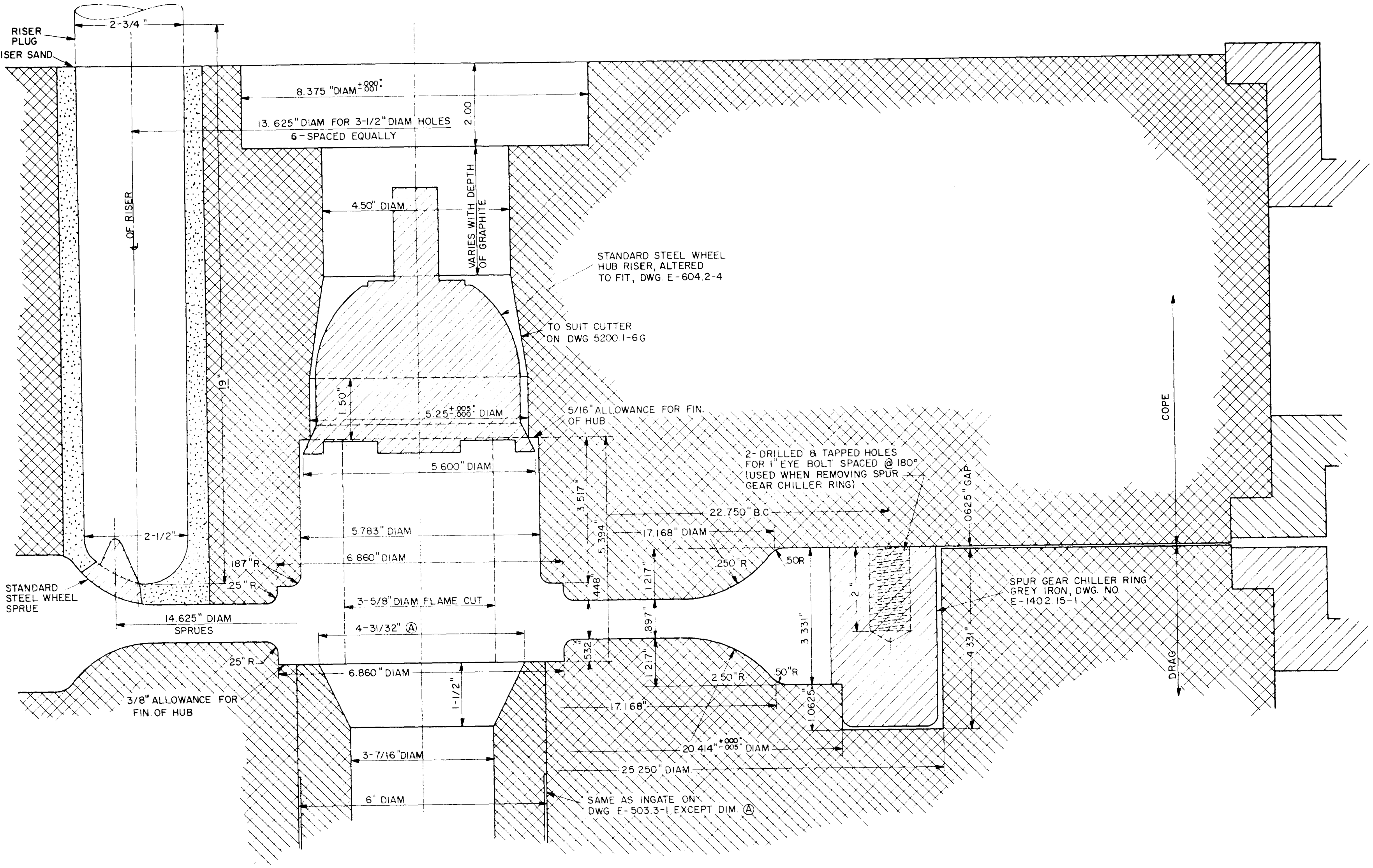


Fig. 17. Permanent mold design for precision-cast final drive gear, Part No. 7364141.

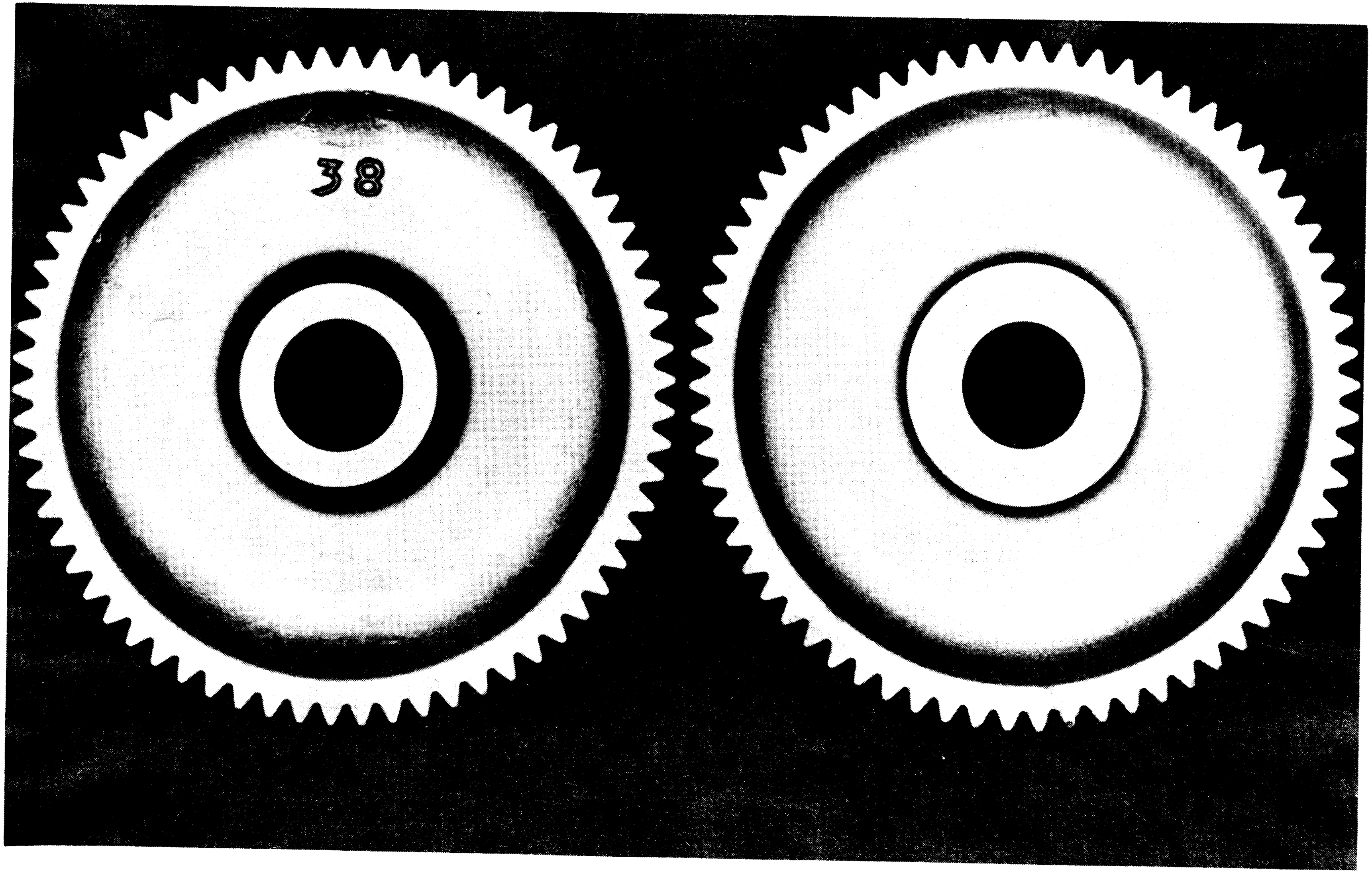


Fig. 18. Precision cast AISI 1062 final drive gear, Part No. 7364141.

Fig. 19. Precision-cast AISI 4817, Part No. 7364141, with pinion ready for test.

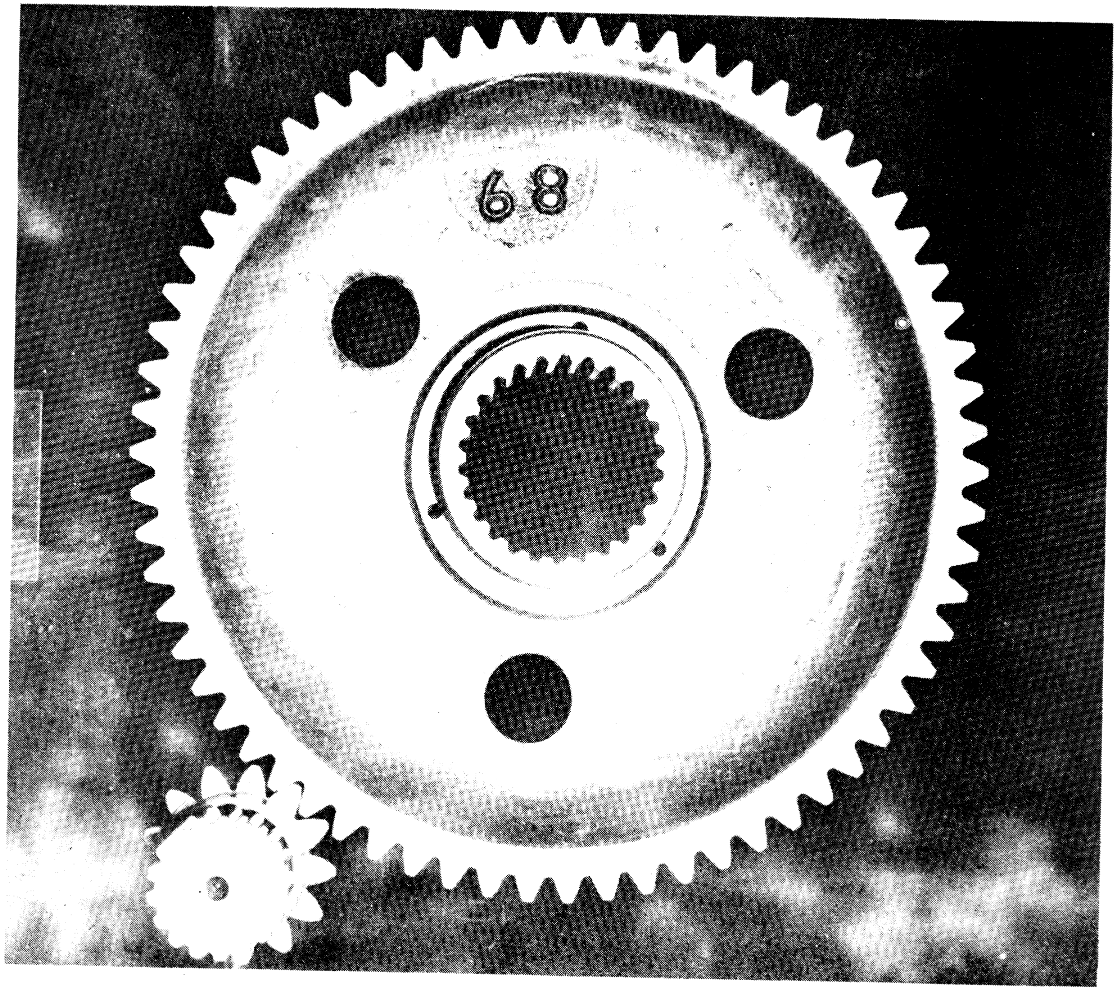


Figure 19. Precision-Cast AISI 4817, Part No. 7364141, with Pinion Ready for Test.

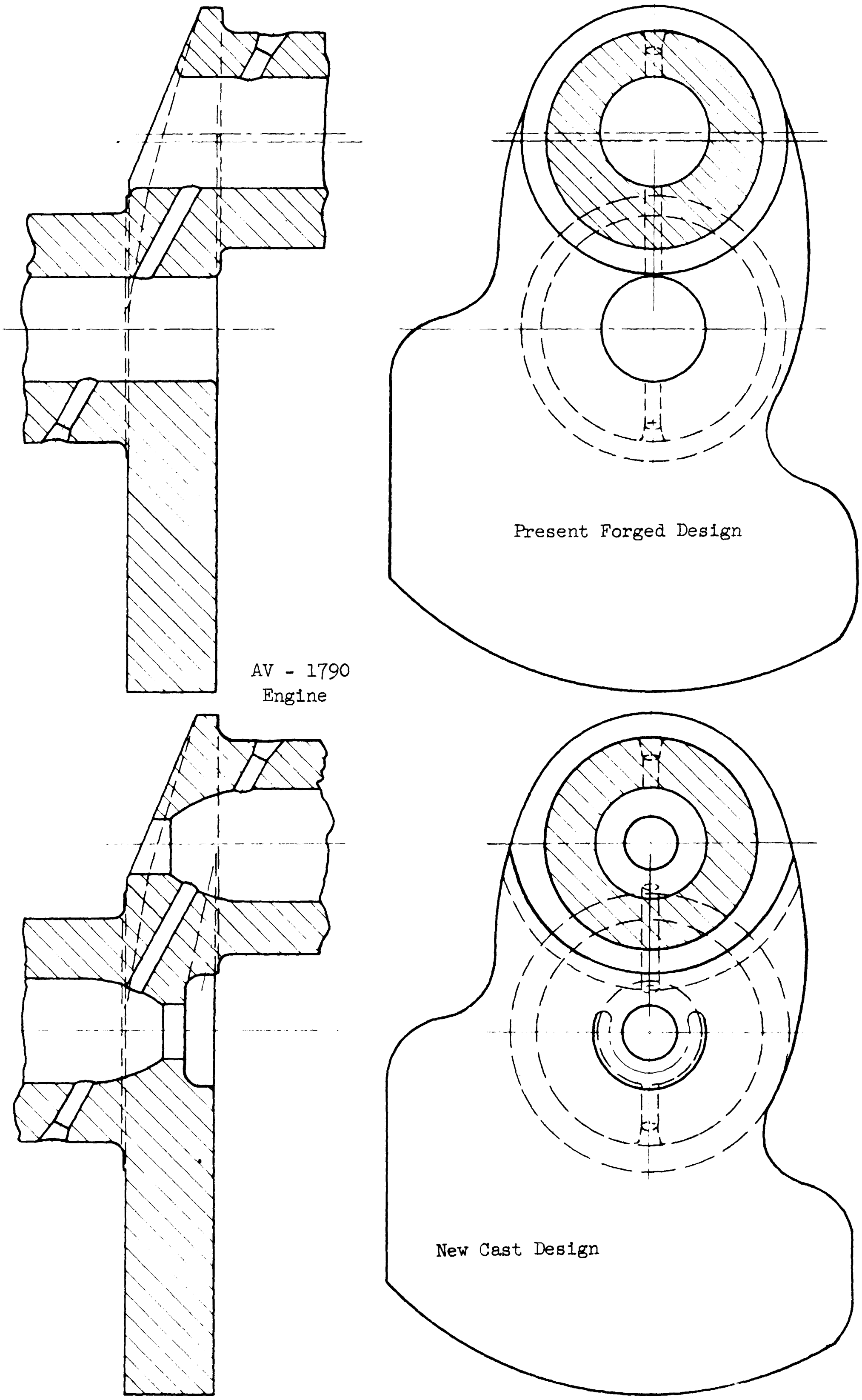


Figure 20. Cast and Forged Crankshaft, AV-1790 Engine.

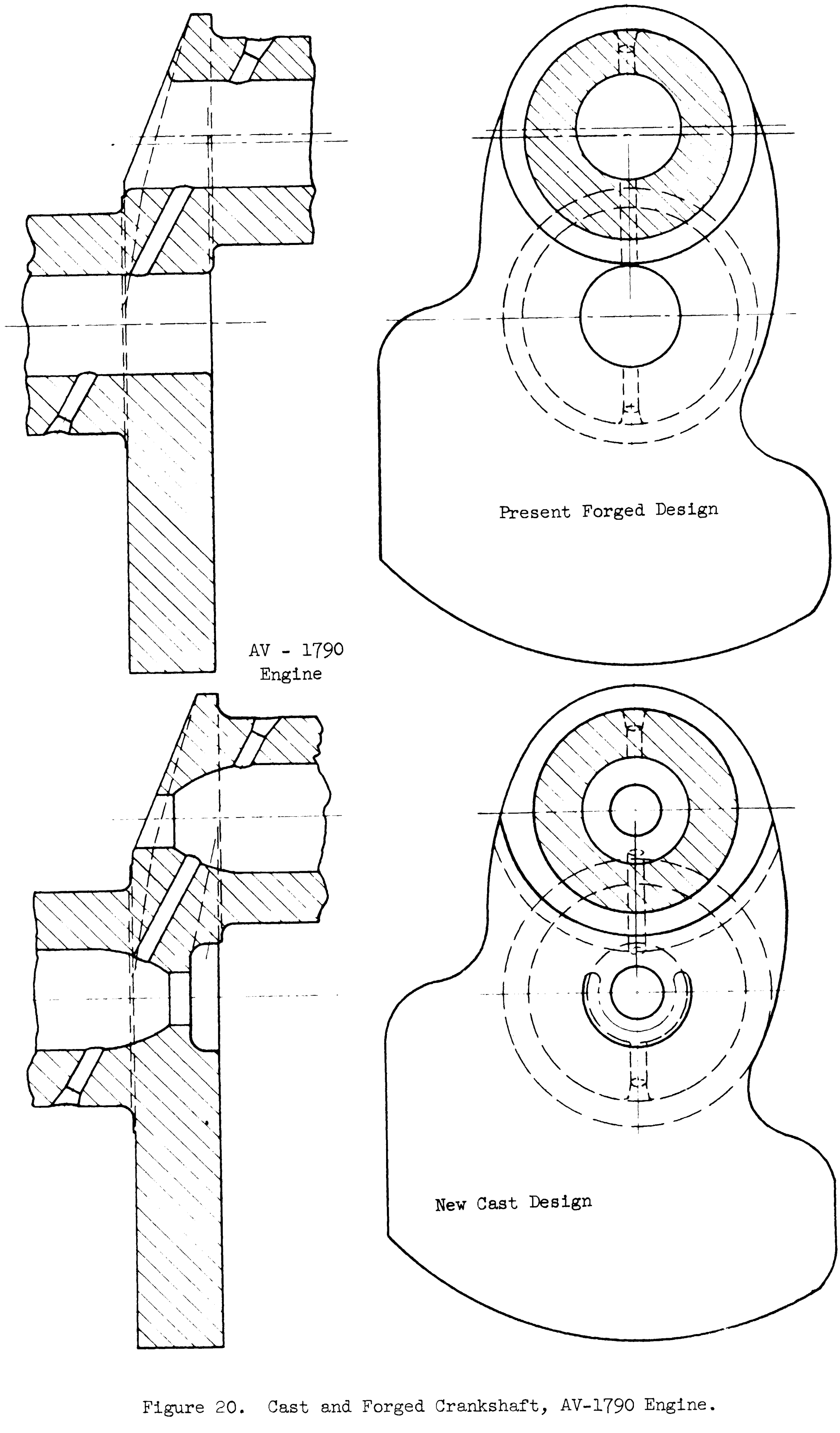


Figure 20. Cast and Forged Crankshaft, AV-1790 Engine.

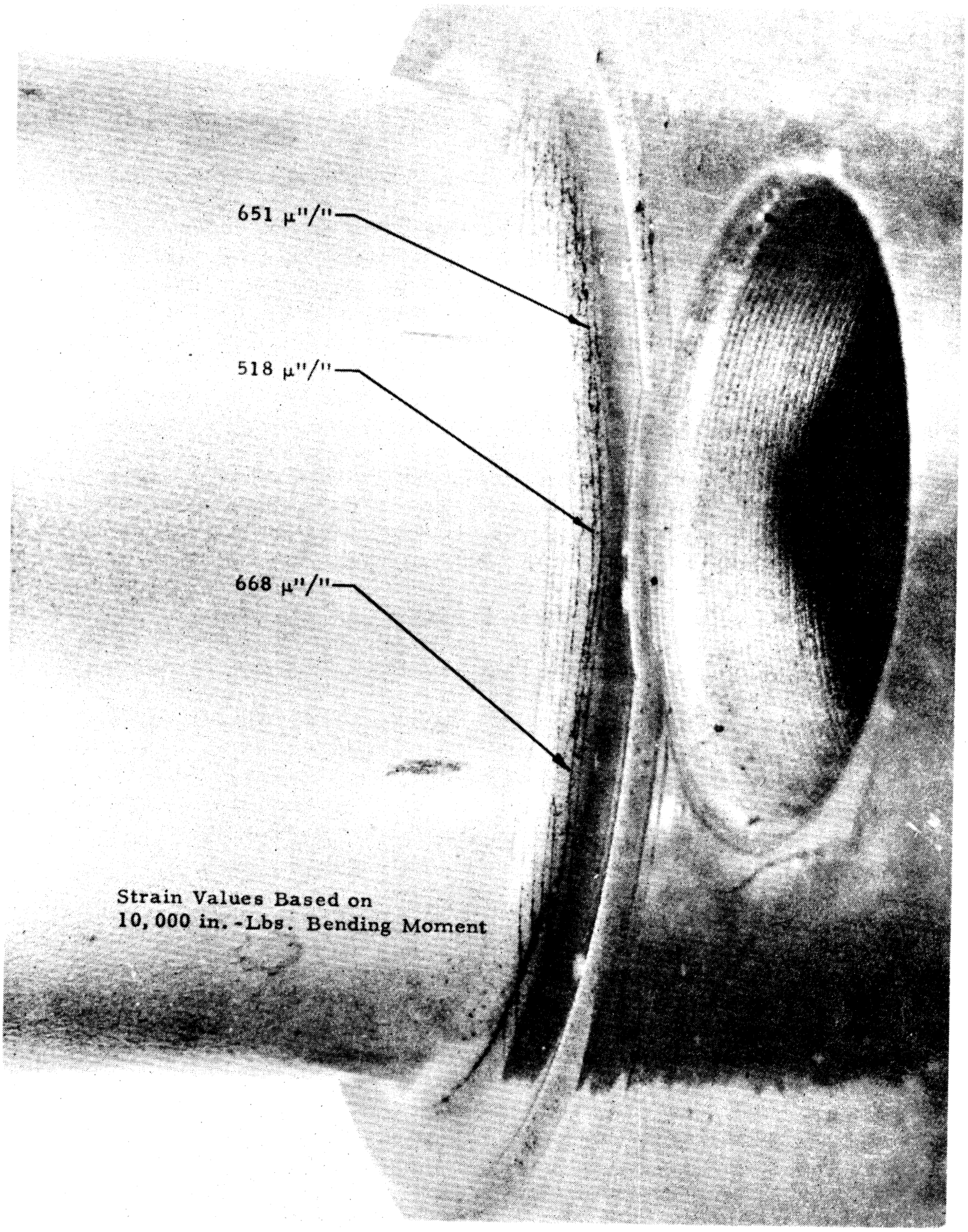


Figure 23. Stresscoat Pattern on Present Design, Forged Crankshaft, P/N 529083 - S.L. 258.

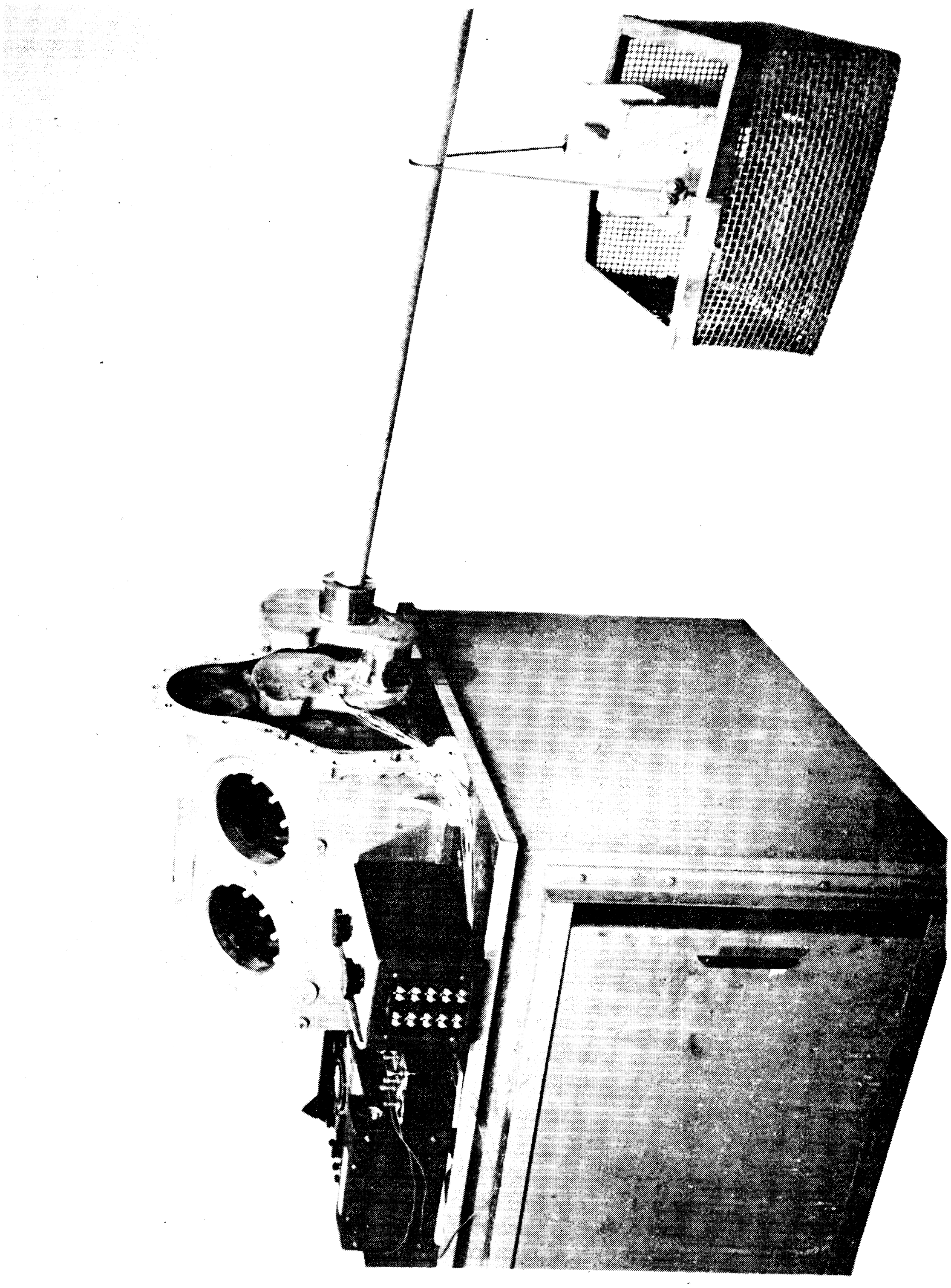


Figure 22. Test Set-Up for Experimental Cast Steel Crankshaft Design S.L. 258.

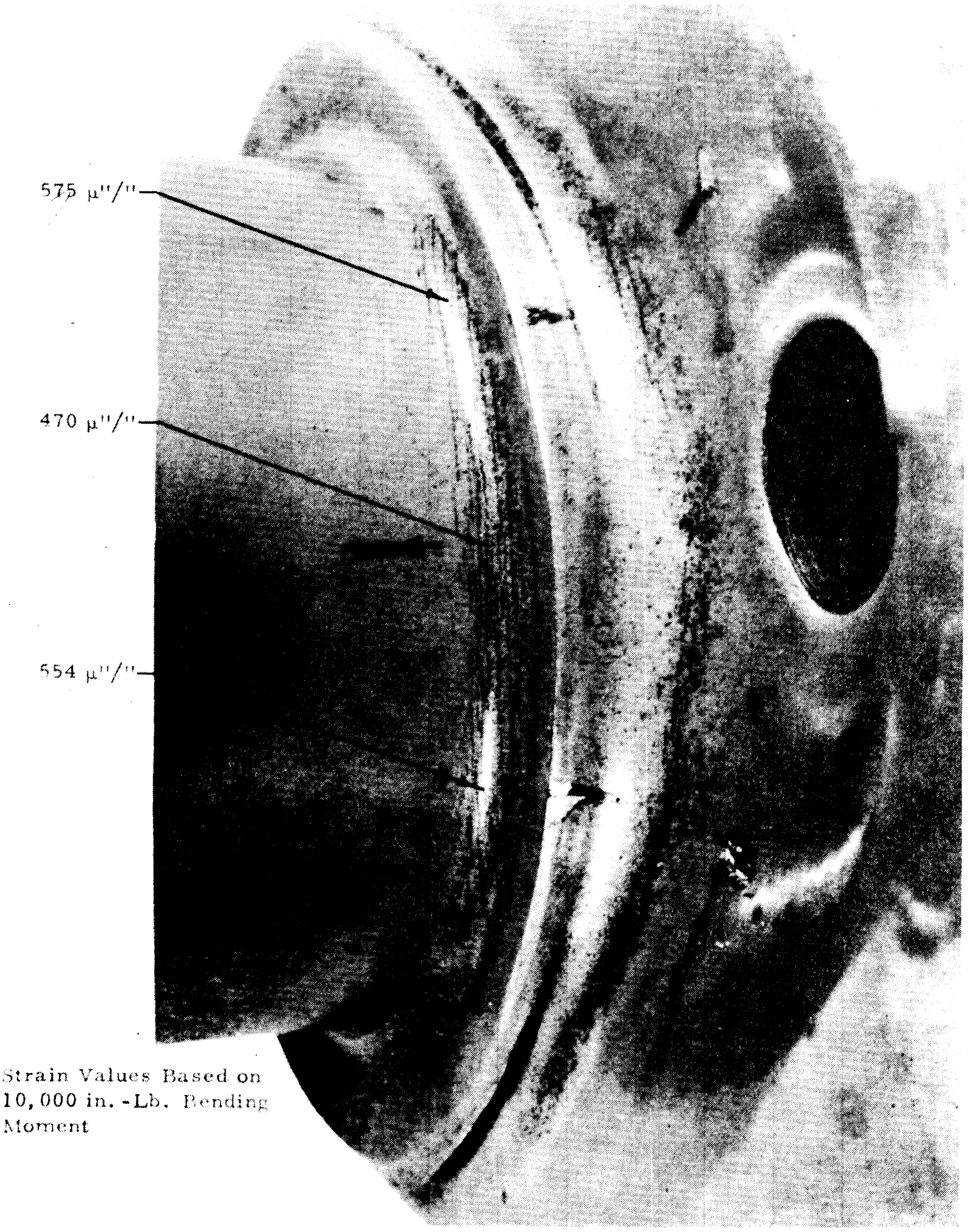


Figure 24. Stresscoat Pattern on Experimental Cast Steel Crankshaft (Modified Fillet) S.L. 258.

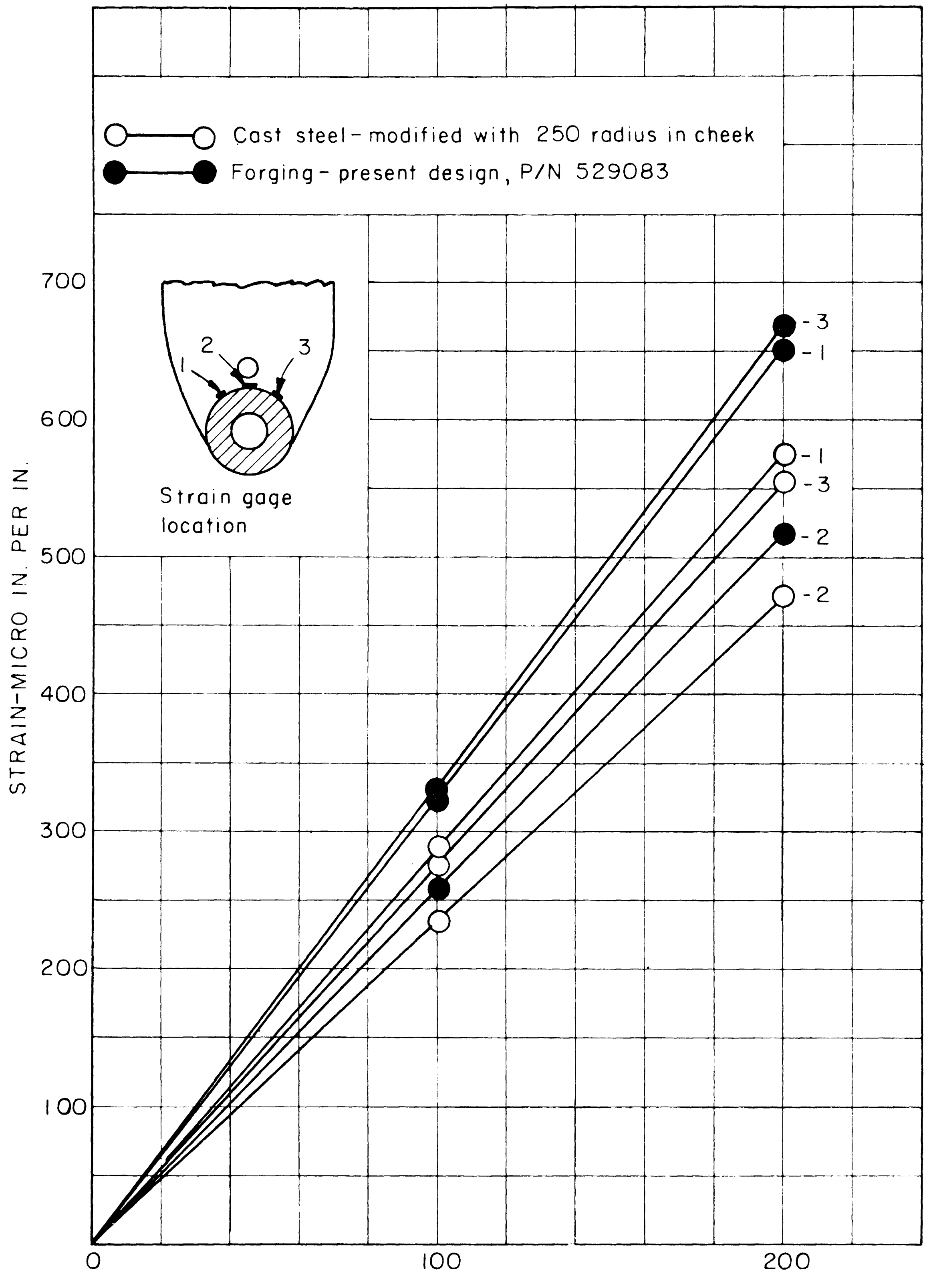
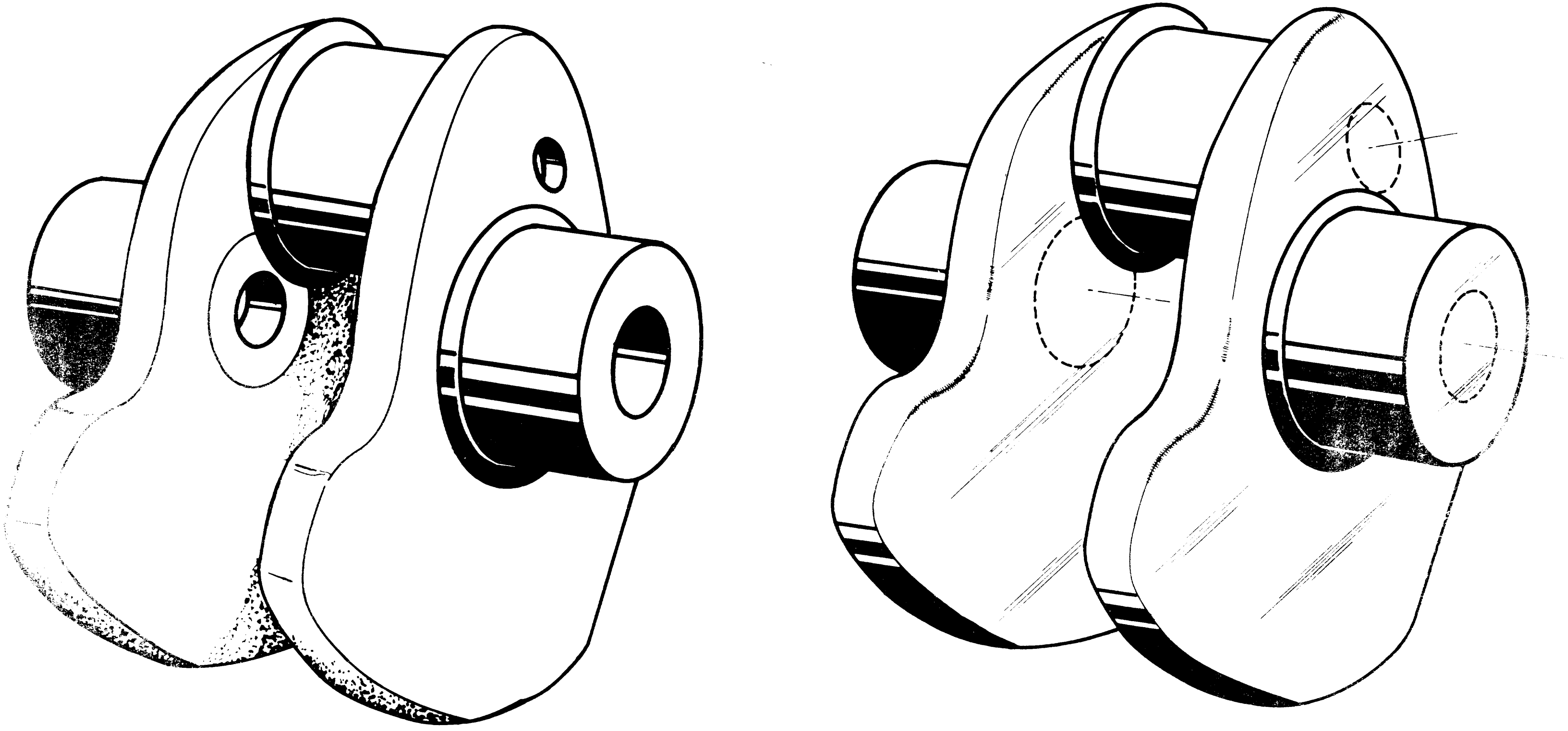


Fig. 25. Strain vs. bending load for cast and forged design crankshaft, AV-1790 engine.



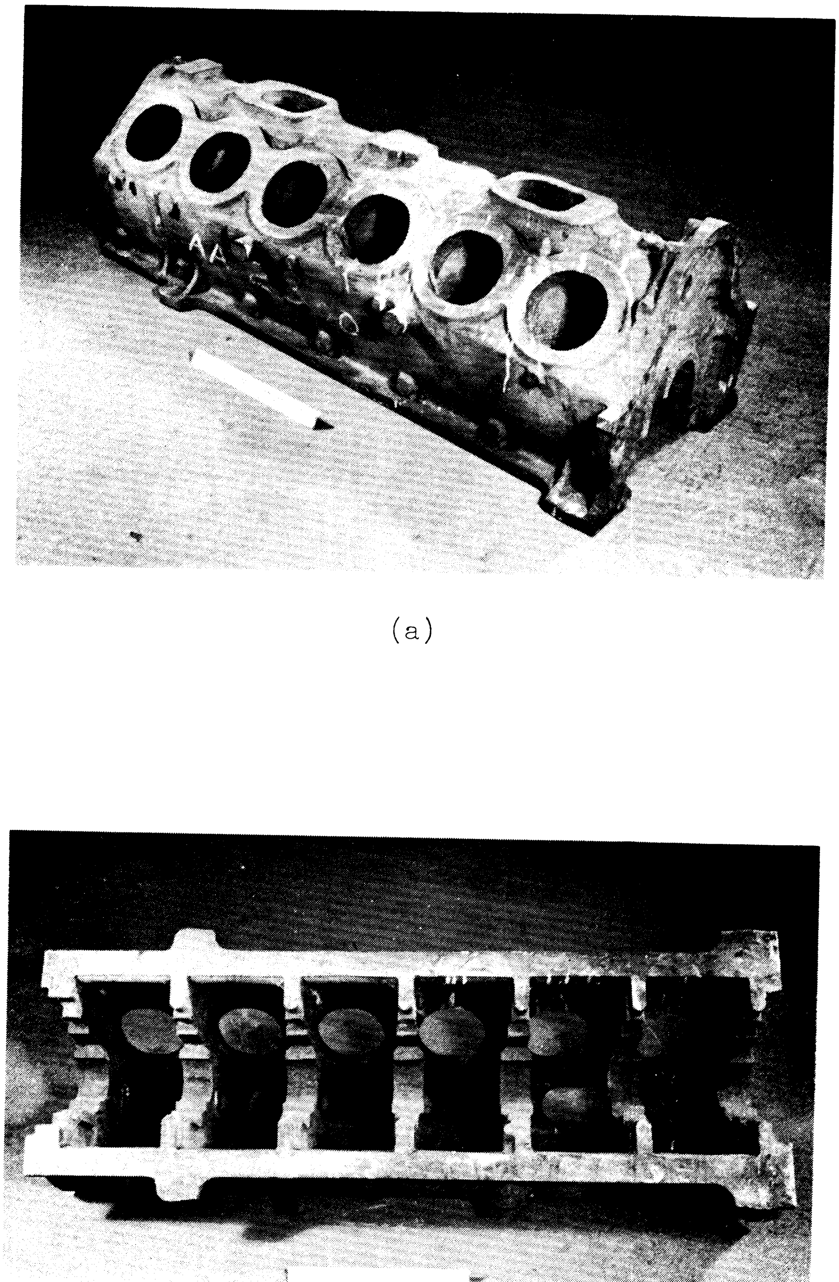
Bearing surfaces machined

CAST CRANKSHAFT

All surfaces machined

FORGED CRANKSHAFT

Fig. 26. Comparative machining required for cast vs. forged crankshaft, Part No. 8717056.



(a)

(b)

Fig. 27. Sand-cast aluminum-alloy crankcase for AV-1790 engine.

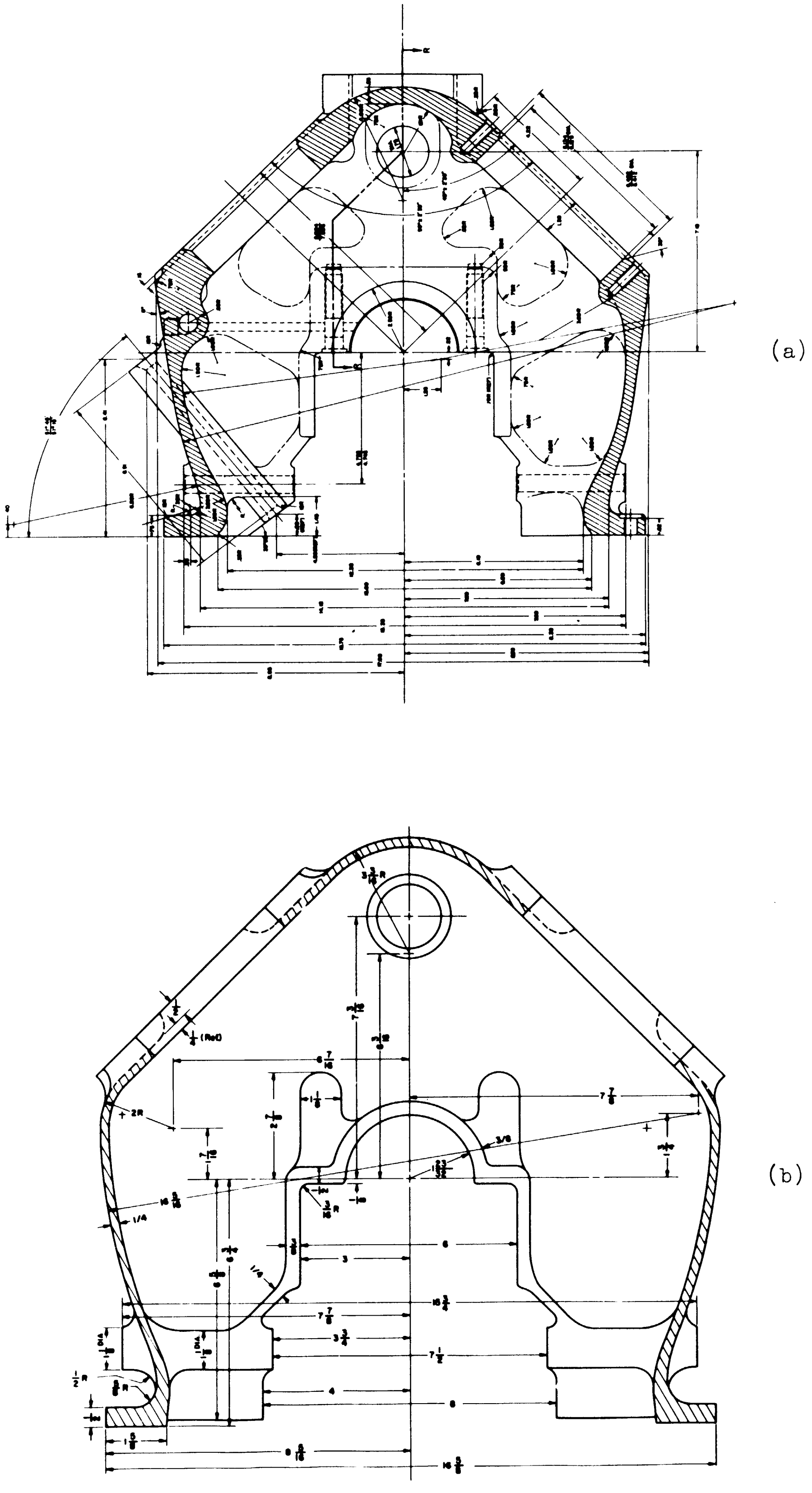


Fig. 28. Section of (a) present sand-cast aluminum-alloy crankcase for AV-1790 engine, and (b) new cast ferrous-alloy crankcase.

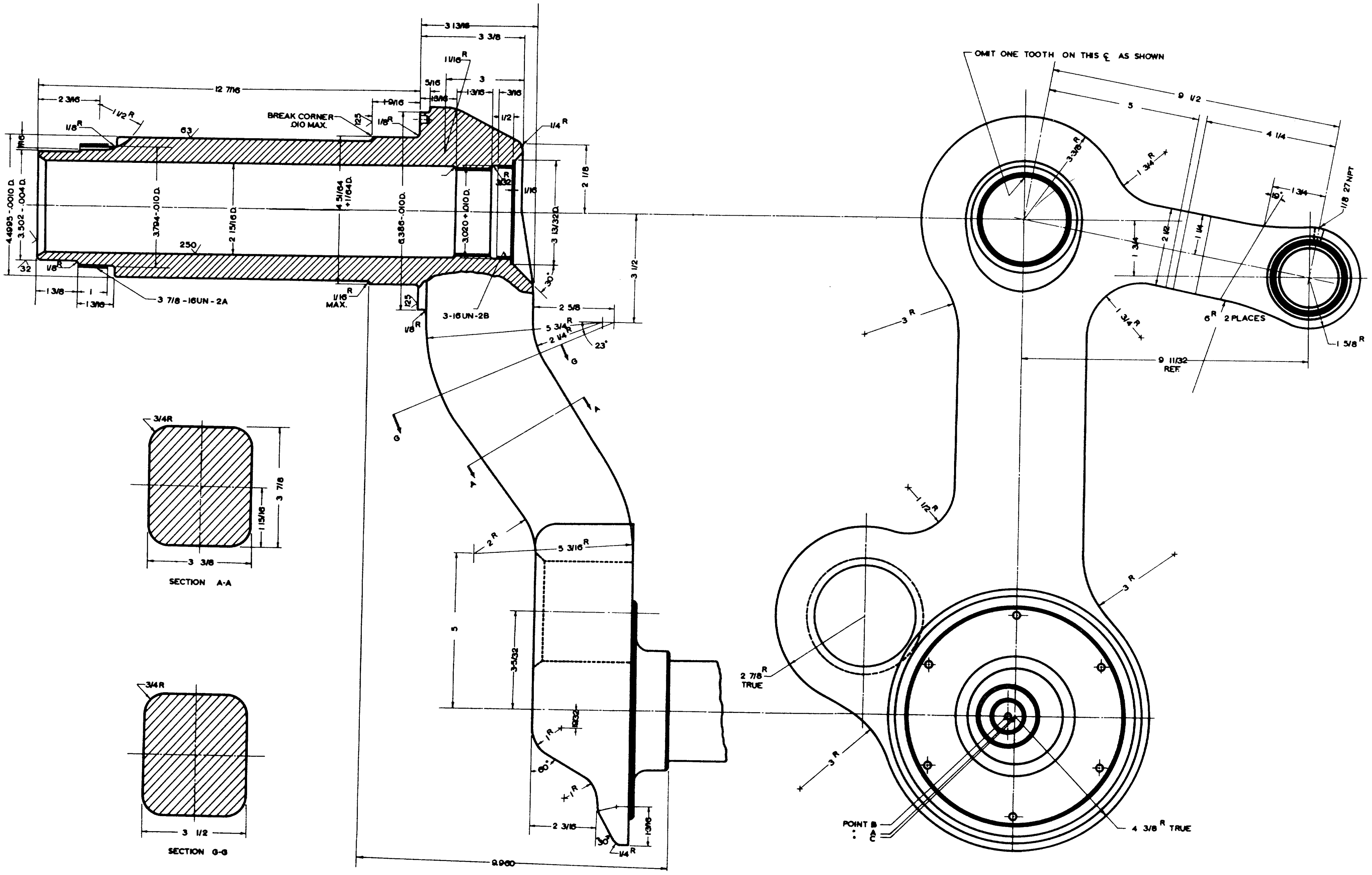
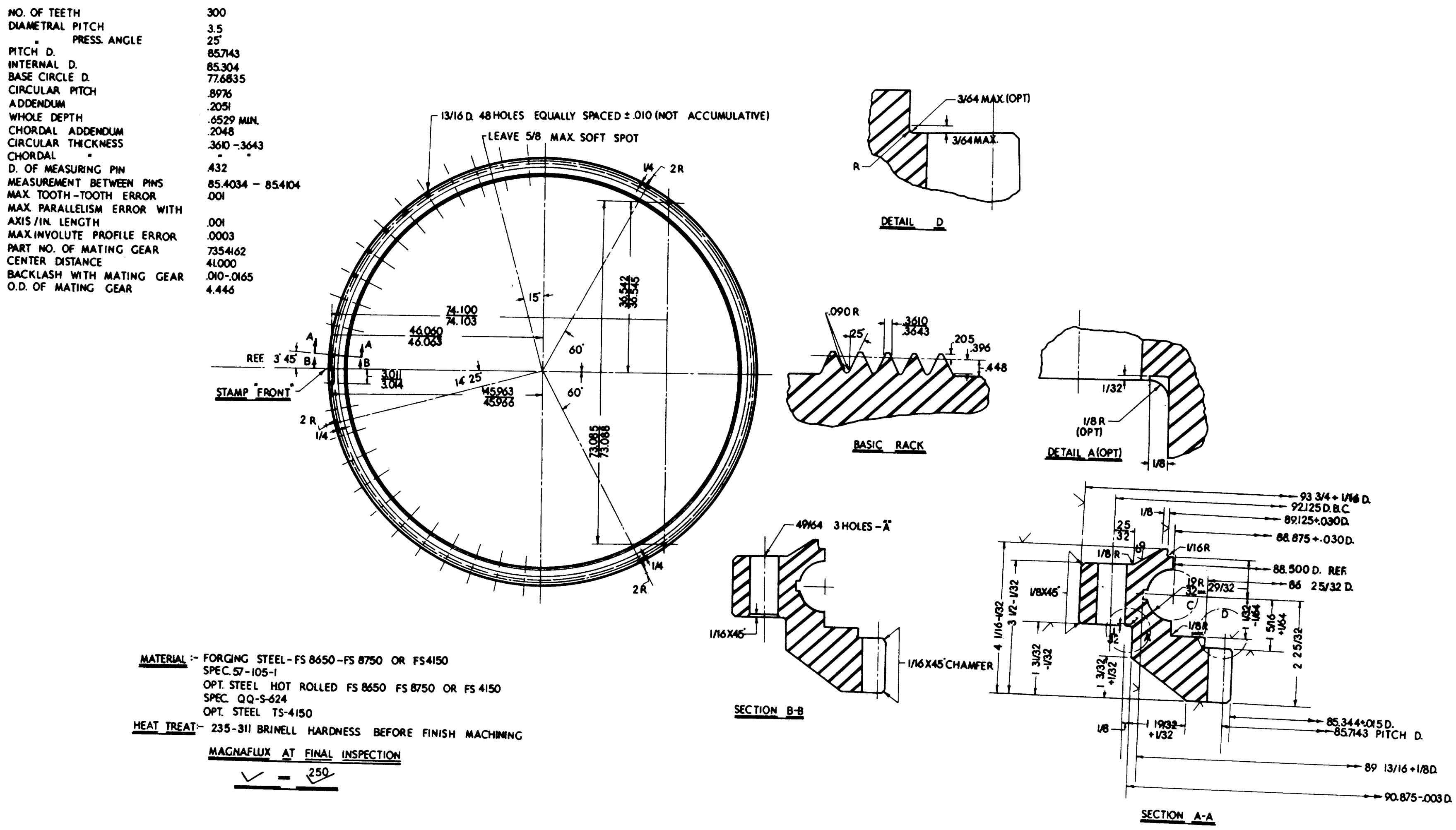


Fig. 29. Suspension and spindle arm, Part No. DTA 15910-15.



NO. OF TEETH	300
DIAMETRAL PITCH	3.5
" PRESS. ANGLE	25°
PITCH D.	85.7143
INTERNAL D.	85.304
BASE CIRCLE D.	77.6835
CIRCULAR PITCH	.8976
ADDENDUM	.2051
WHOLE DEPTH	.6529 MIN.
CHORDAL ADDENDUM	.2048
CIRCULAR THICKNESS	.3610 - .3643
CHORDAL "	" "
D. OF MEASURING PIN	.432
MEASUREMENT BETWEEN PINS	85.4034 - 85.4104
MAX. TOOTH-TOOTH ERROR	.001
MAX. PARALLELISM ERROR WITH AXIS/IN. LENGTH	.001
MAX. INVOLUTE PROFILE ERROR	.0003
PART NO. OF MATING GEAR	7354162
CENTER DISTANCE	41.000
BACKLASH WITH MATING GEAR	.010-.0165
O.D. OF MATING GEAR	4.446

MATERIAL:- FORGING STEEL - FS 8650 - FS 8750 OR FS4150
SPEC. 57-105-1
OPT. STEEL HOT ROLLED FS 8650 FS 8750 OR FS 4150
SPEC. QQ-S-624
OPT. STEEL TS-4150

HEAT TREAT:- 235-311 BRINELL HARDNESS BEFORE FINISH MACHINING

MAGNAFLUX AT FINAL INSPECTION

✓ = 250✓

Fig. 30. Outer race, Part No. 7384006.

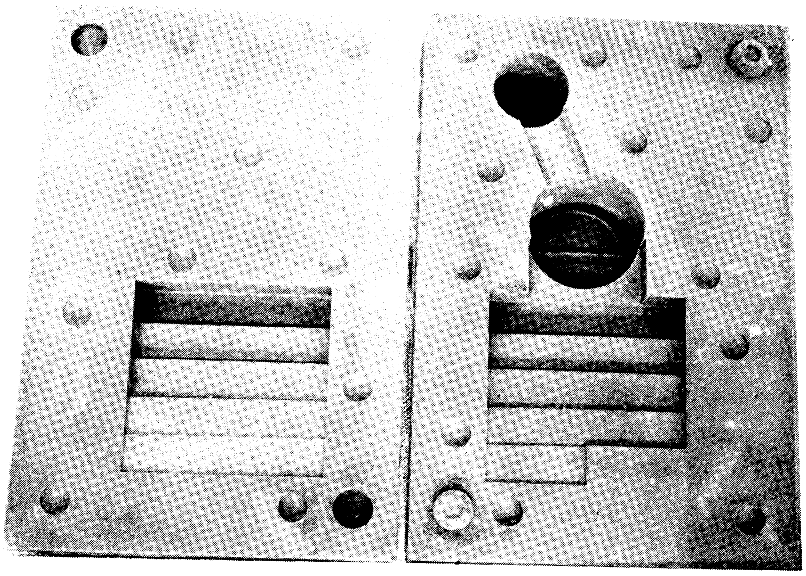


Fig. 31. Mating surfaces of small shell step mold.

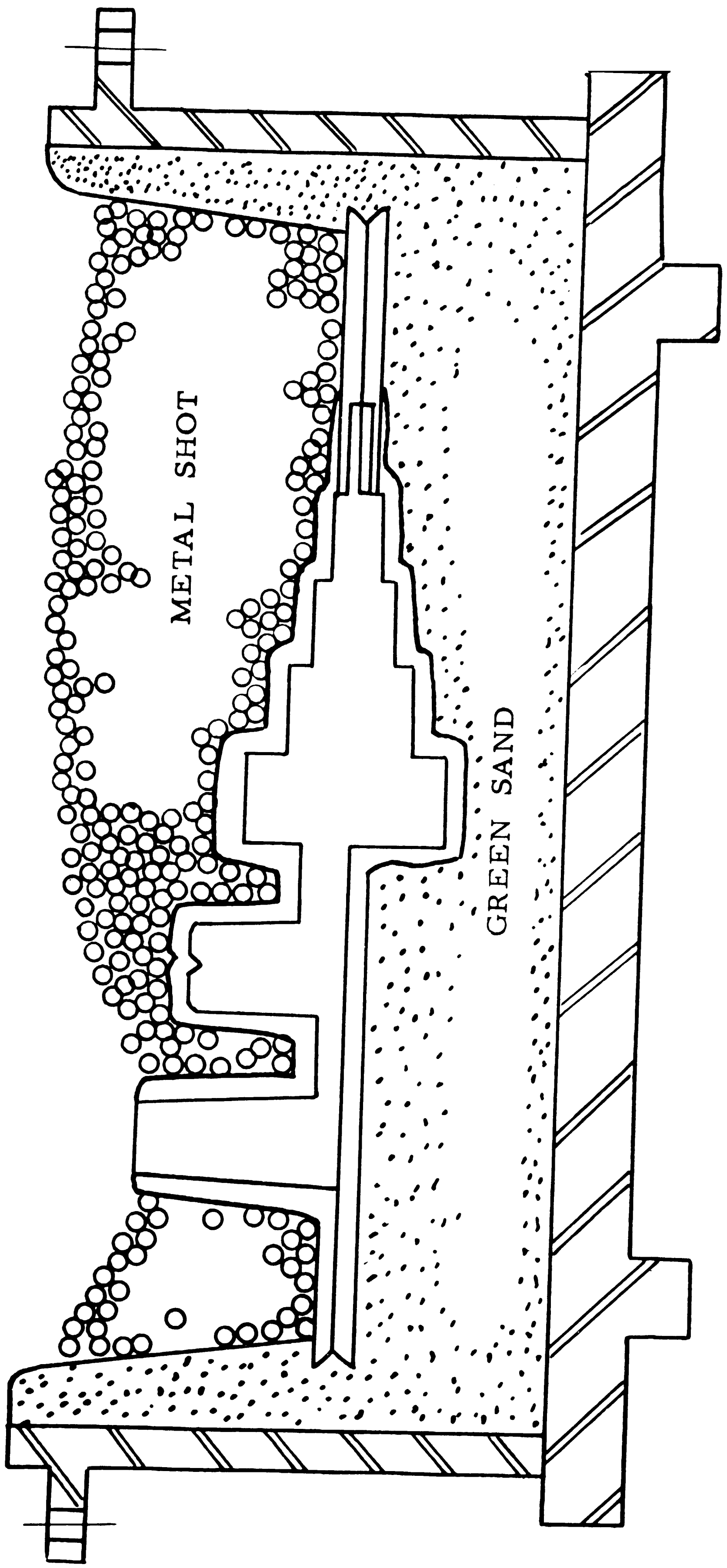


Figure 32. Cross Section of Assembled Shell Step Mold.

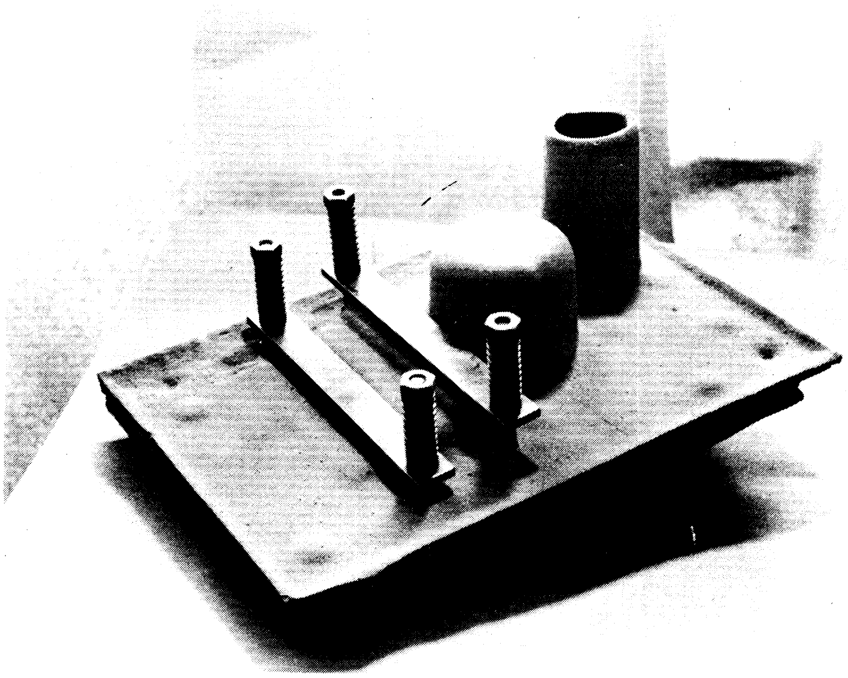


Fig. 33. Calibrated spring clamps.

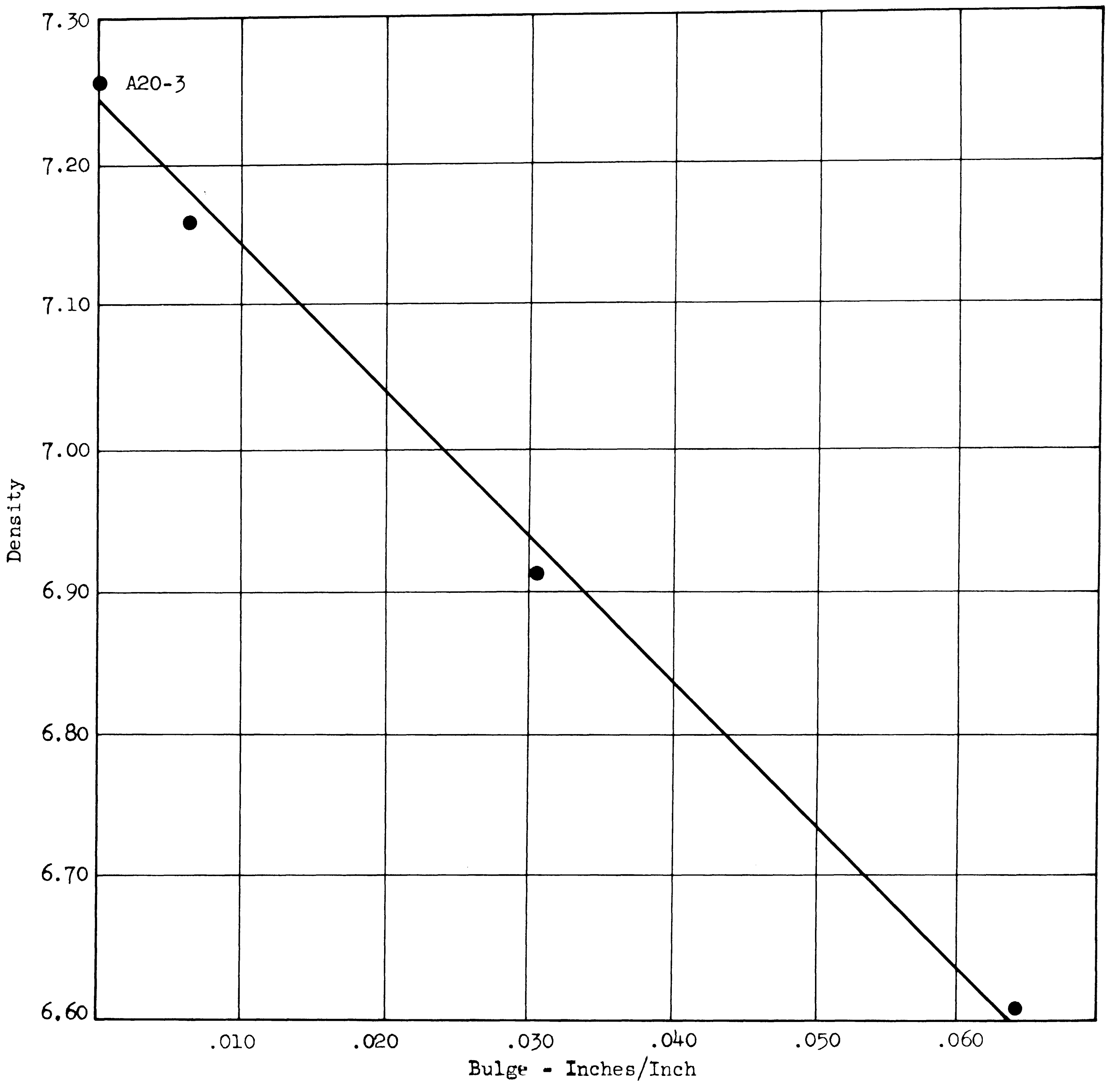


Fig. 34. Casting density vs bulge of 2-inch step for unrisered castings.

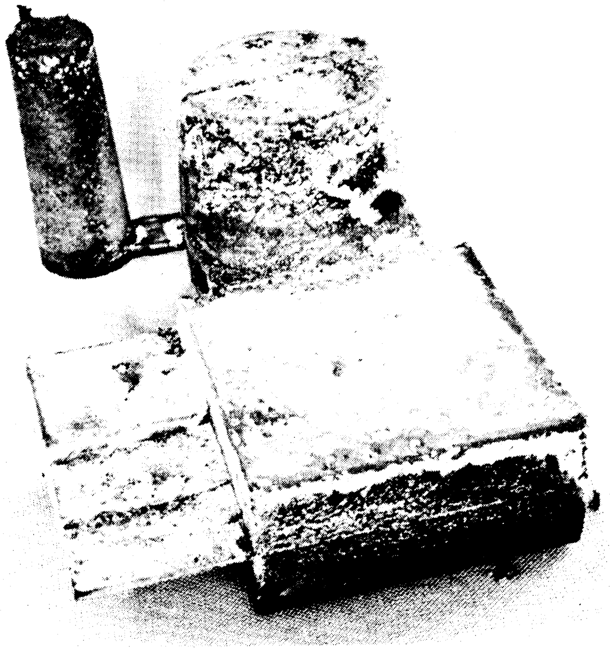


Fig. 35. Surface defect caused by SiO_2 reduction.

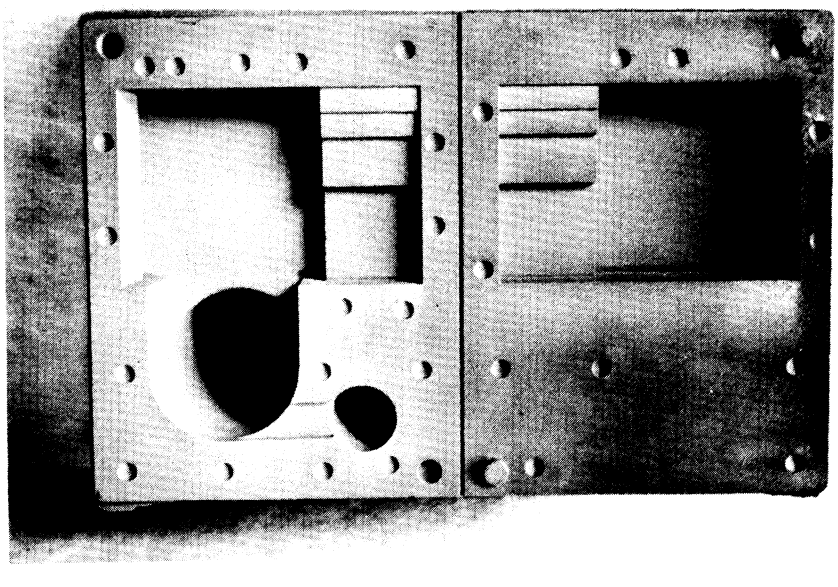


Fig. 36. Mating surfaces of large shell step mold.