LA-12369-MS

C. 3

The Potential of Investment Casting for the Production of Near Net Shape Uranium Parts

Los Alamos
NATIONAL LABORATORY

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

LA-12369-MS

UC-706 and UC-721
Issued: September 1993

The Potential of Investment Casting for the Production of Near Net Shape Uranium Parts

*Erica Robertson**

**United States Air Force Academy*
Materials Division, Department of Engineering Mechanics
HQ USAFA/DFEM, Fairchild Hall,
Colorado Springs, CO 80840.

Los Alamos
NATIONAL LABORATORY
Los Alamos, New Mexico 87545

THE POTENTIAL OF INVESTMENT CASTING FOR THE PRODUCTION OF NEAR NET SHAPE URANIUM PARTS

by

Erica Robertson

ABSTRACT

This report was written to provide a detailed summary of a literature survey on the near net shape casting process of investment casting. Investment casting is one of the near net shape casting technologies which has the potential to satisfy the requirements of the LANL program titled Near Net Shape Casting of Uranium for Reduced Environmental, Safety and Health Impact. In this report, the advantages and disadvantages of this casting process are reviewed and an assessment of the ability to achieve the near net shape and waste minimization goals of the LANL program by using this technique is made. Based upon actual past experimental research results and the ability to integrate automation and recycling into the process, investment casting appears to be an attractive process for achieving the goals of near net shape casting with subsequent hazardous waste minimization.

I. INTRODUCTION

The purpose of this report is to describe the investment casting process and to determine the viability of using this technique to achieve near net shape uranium and uranium alloy products with subsequent minimization of hazardous waste. This paper begins with a general description of the investment casting process and is followed by sections discussing both the advantages and disadvantages associated with the process. Specific areas addressed are part complexity, freedom of alloy selection, close dimensional tolerances, availability of prototype and temporary tooling, reliability, wide ranging applications, the ability to minimize waste by recycling mold materials, process automation capabilities, factors contributing to casting cost, and finally problems associated with casting density, shrinkage and distortion. A brief mention is then made of a U.S. Army study conducted in 1987 in which U.S. industrial casting firms were surveyed to assess their ability to support the U.S. Armed Forces during periods of peacetime, surge, and mobilization. This is followed by a summary of some past experimental research on the investment casting of uranium and concluded with a section on the potential use of this casting technique to achieve the goals of near net shape processing with subsequent hazardous waste minimization when casting uranium or uranium alloys.

II. PROCESS DESCRIPTION

This technique, also referred to as the lost-wax process, uses a disposable pattern (usually wax) which is coated with a ceramic slurry and allowed to harden to form a disposable casting mold. Disposable here means that the pattern is destroyed during its removal from the mold and that the mold is destroyed to recover the casting. Fig. 1 diagrams the steps involved in the investment casting process which include pattern making and assembly, investing, stuccoing, dewaxing, firing, pouring, knockout, finishing and inspection.[1] The pouring step is sometimes combined with vertical centrifugation in which the centrifugal force assists in feeding molten metal to the mold cavities.

III. ADVANTAGES

The major advantages of the investment casting process are discussed below:

A. Part Complexity

Parts previously made by assembly of many individual components can be made as integral castings at much lower costs and often with improved functionality. For example, the turbine frame in the F110 engine, which powers the Air Force's F-16 fighter aircraft, consists of 62 separate fabricated parts. But, this multi-part structure is being replaced by a single investment casting.[2]

B. Freedom of Alloy Selection

Any castable alloy can be used, including ones that are difficult to forge or are too difficult to machine. The cost of the alloy is less important in the final price of the investment casting than for other metal-forming processes. This allows for an upgraded alloy to be specified at little or no price increase.

C. Close Dimensional Tolerances

The absence of parting lines and elimination of substantial amounts of machining by producing parts very close to final size allow for achieving close dimensional tolerances which cannot be achieved by other casting or forging processes. In a publication by Arwood Corporation, several guidelines for casting design are given to emphasize the fact that the more attention that is paid to initial part design, the less you need to worry about end machining and finishing operations.[3] Some of the basic design rules to follow are:

1. Contour Shape: Curved and blended contours make for stronger designs than straight lines and abrupt angles and usually cost less.

2. Surface Finishing: When designing for finishing, where surfaces aren't critical, design for the process. Where they are, leave ample stock so that you can get below the as-cast surface with your finishing operation. Leaving enough stock is particularly important when considering machine finishing; users of investment castings have found that they can cut set-

up time and lengthen tool life when there is enough extra metal to let the tool get below the somewhat abrasive casting surface as quickly as possible.

Additional tolerance information concerning radii, straightness, flatness, concentricity, roundness, angles, parallel sections, and holes is also given in Arwood's report along with specific design information concerning size, weight, minimum section thickness, serrations, holes, surface finish, threads, gating, draft and fillets.

D. Availability of Prototype and Temporary Tooling

The direct machining of wax patterns facilitates timely collaboration between the designer and the foundry to produce parts that are functional and manufacturable, a major advantage in the design and evaluation of parts. This capability (concurrent/rapidly iterative engineering) is simply not found for such competitive processes as die casting, powder metallurgy, or forging.

Another aspect to consider in prototype and tooling design is cost. Initial cost estimates related to investment casting are often relatively high. This is usually the result of a cost estimator's rapid review of an engineering drawing, estimated cost of tooling plus an inflation factor to cover oversights caused by not having the time necessary to thoroughly review the casting designs in detail prior to price quoting. To reduce the often inflated tooling and unit costs for investment castings, the Bendix Corporation investigated the use of SynthaVision, a three-dimensional solid modeling program.[4] With the SynthaVision program, three-dimensional photos were generated for new investment casting designs. These photos served as procurement aids which significantly eliminated a lot of guesswork on the part of the cost estimators who usually generated tooling and unit costs based only on detailed engineering drawings. Bendix has successfully implemented SynthaVision on several investment castings and realized cost avoidance benefits. It was also suggested in the report that this technique could be used for quoting, designing and fabricating gaging, machine tooling, and fixturing.

E. Reliability

The long-standing use of investment castings in aircraft engines for the most demanding applications has fully demonstrated their ability to be manufactured to the highest standards.

F. Wide Range of Applications

Complex parts with stringent requirements as well as very simple parts can both be made competitively. This is often made possible by the low cost of tooling associated with investment casting as compared to other fabrication techniques such as die casting or forging. Investment castings are produced competitively in sizes ranging from a few grams to more than 300 kg (660 lb) and the upper limits continue to increase.

G. Waste Minimization and Mold Recycle Capability

Such measures as calculating the thermal durability of the investment molds contribute to waste minimization by ensuring proper mold design to avoid cracking and the subsequent production of a scrapped casting.[5] Selection of reusable mold materials can also help to minimize waste. Some waxes are even recycled.[6-8] Investment molds containing zircon were developed in the early 1980's for titanium and molybdenum castings.[9,10] The zircon in these mold materials may be recycled.

In 1985, the Bureau of Mines conducted research to devise technology for recovering zircon from waste investment casting molds. The recovery of zircon would allow the investment casting process to be more economical for high-volume, low cost articles and also help conserve domestic resources and reduce dependence on foreign supplies. The Bureau of Mines[11] investigated three methods of beneficiation to obtain zircon concentrates from the waste investment casting molds. Froth flotation followed by caustic leaching and magnetic separation yielded concentrates containing up to 74.2% zircon with a recovery of 53.4%. Gravity concentration by tabling followed by caustic leaching and magnetic separation yielded the highest concentration of zircon at 98.6%; however the recovery was only 57%. The most promising technique proved to be the method of caustic leaching and sizing which yielded concentrates of up to 98% with a recovery of 81%.

H. Process Automation Capability

In 1959, the U.S. Army developed a method for the application of solid, granular particles in the build-up of an investment casting mold using fluidized particle beds.[12] Since then, with the advent of robotic technology, several procedures involved in the investment casting process have been modified to incorporate automation or robotic methods.[13-18] For example, in the production of investment shell molds, the operations of investing and stuccoing are often handled by robots. Pratt & Whitney's Automated Casting Facility (ACF) at Middletown, CT is an example of the use of robotics for this purpose.[19] The ACF is billed as the only investment casting facility of its kind in the world, using computers to monitor some 4000 operational functions simultaneously to ensure consistent high quality in the gas turbine blades it produces. The robots used for the preparation of shell molds have grippers which incorporate infrared sensors for checking both workpiece presence/absence and jaw position. They also provide a continuous-spin rotation to ensure uniform powder/sand deposition on the shells. The combination of smooth robotic motion and this unique gripper have resulted in a 300% reduction in scrap mold material as compared to earlier generation robotic equipment. The fact that robots are used, however, does not make the human obsolete. Operators are needed to monitor the temperature and humidity of the mold preparation room and the process equipment.[20]

IV. DISADVANTAGES/PROBLEMS

There are a few disadvantages of the investment casting process such as the final cost of an investment cast part, which is often relatively high. One factor contributing to the high cost is the fact that the casting molds are not reusable. However, the cost of making new shell molds could be decreased by recycling the zircon from the used mold materials. Other measures can also be taken to reduce the final cost of investment castings such as proper gating design[21] or the use of computer modeling to optimize the casting process.[2]

Although surface finish of investment castings is often superior to castings produced by other techniques, sometimes there is difficulty in achieving sound castings. Porosity in investment castings can occur if the gating system is designed such that proper metal feed is not established for the particular freezing range of the metal or alloy.[22] Porosity can form by nucleation and growth in castings when the feeding mechanisms (liquid feeding, liquid plus solid (mass) feeding, burst feeding, interdendritic feeding and solid feeding) become inadequate to compensate for solidification shrinkage. However, porosity problems can be avoided with proper casting/gating design.[23]

Another problem which was mentioned in the literature was that of dimensional distortion. Rolls-Royce examined the causes of dimensional distortion in directionally solidified, cored, turbine blades made from investment cast superalloys.[24] Observation of their scrap materials revealed that the majority of the problems of rejected parts were in areas of dimensional reproducibility, specifically wall thickness and core related problems. In a comprehensive study of their investment casting procedures, Rolls-Royce was able to pinpoint the various stages in the process which led to distortion and recommended steps to be taken to improve the situation such as: better training of personnel controlling the manual operations, restricting movements of cores by chapletting or using p-pins, and automating inspection systems. There has also been some work on prediction and simulation of shrinkage formation in investment castings by the Japanese.[25] Shrinkage was found to be related to solid fraction gradients and alloy chemistry.

V. RESULTS OF 1987 U.S. ARMY SURVEY OF INVESTMENT CASTING FIRMS

In 1987, the U.S. Army conducted an industrial survey of U.S. casting firms to assess the ability of the investment casting industry to support the U.S. Armed Forces during peacetime, surge and mobilization.[26] Although some problems were identified (e.g. high labor intensity, possible long lead times, shortages or critical materials), the overall conclusion was that the state of the investment casting industry was adequate to meet defense requirements.

VI. EXPERIMENTAL RESEARCH ON THE INVESTMENT CASTING OF URANIUM

Some details of experimental uranium investment casting research are given in a paper published in the 1979 Proceedings of the Sixth International Vacuum Metallurgy Conference on Special Melting.[27] It was mentioned that the Oak Ridge Y-12 Plant had successfully produced investment castings of both depleted uranium and uranium alloys. For this work, melting was carried out in a clam-shell induction furnace with a vacuum capability of 0.7 Pa (5µm, Hg). The following details of the investment casting process were given:

1) "Ceramic shell-making should be conducted under controlled conditions of temperature at a reasonably high relative humidity."

2) "Wax is injected into an aluminum mold at 200 to 500 psi and at a temperature where the wax is semi-solid, typically 55°C. After allowing the mold to come to a uniform temperature, the wax pattern is removed from the aluminum pattern mold, degreased and cleaned."

3) The most successful ceramic shell molds were obtained by using a slip with zircon flour ($ZrO_2.SiO_2$) mixed with 30% colloidal silica binder. To build up the ceramic shell mold thickness, the wax pattern was first wetted with colloidal silica, then coated with zircon-silica slurry, stuccoed with fine zircon sand and dried. This sequence was then repeated until a 5 to 15 mm thick shell was established. After the first few coats, progressively coarser stucco was used.

4) The wax was then melted out of the finished shell mold during a 1000°C bake cycle.

5) "The hot shell molds are then loaded into the furnace and cast. After the mold and castings are removed from the furnace, the mold shell is broken away from the casting. The casting cluster is then cropped and separated. Generally excellent cast surfaces, free of significant mold reaction were obtained using a 900°C mold preheat temperature and mold facings 6-8 mm thick. For higher melting point uranium alloys a yttria base slurry may be required, but for unalloyed uranium the zircon mixture seems adequate."

It was concluded that the investment casting process has promise for producing low cost cast uranium shapes. However, the authors state that the economics of the process has not been rigorously established.

VII. CONSIDERATIONS IN THE APPLICATION OF INVESTMENT CASTING TO URANIUM AND URANIUM ALLOYS

The preliminary research mentioned in the above section was driven by the potential of a low cost fabrication method yielding a near net shaped product. However, this is not the only benefit to be gained by using investment casting for uranium or uranium alloys. With increased emphasis on reducing the amount of hazardous waste generated during the fabrication of a uranium part, for environmental, safety and health related reasons, the near net shape aspect of investment casting is attractive as a waste minimization technique as well. There is also the added potential benefit of being able to recycle used investment molds and pattern waxes which would lead to further cost savings and waste reductions. The investment casting process could be a very viable technique for the production of near net shape uranium and uranium alloy parts. The following considerations and recommendations should be incorporated into the individual steps of the investment casting process to achieve a combination of near net shape production and waste minimization:

1. Part Design: In this critical stage of the process, attention must be paid to dimensional tolerances and part geometries. If the as-cast surface will need finish machining, there must be enough material stock available so that subsequent machining operations are able to get below the as-cast surface. Also, if the part is complex, some attention should be given to how the part will fit into any machining fixtures. It might be advantageous to design certain areas or surfaces so that later fixturing problems may be avoided. This stage of part design may be aided tremendously by the use of computer modeling to analyze the response of solidification with respect to heat transfer effects dependent upon mold (part) geometries and material properties. With the finite element methods incorporated into such modeling codes as FLOW-3D, much time and cost can be saved by

avoiding design geometries which could lead to density problems and other casting defects.

2. Wax Pattern Production: Once a part design is finalized, a wax pattern needs to be made. This may entail the purchase of equipment for wax injection molding and the associated dies needed to produce the pattern or the contracting of such services. A wax composition should also be selected (for further information on investment casting waxes see reference 1), preferably one which may be recycled. Other considerations are the determination of the pressure and temperature to be used during the wax injection molding process and the establishment of the appropriate degreasing and cleaning procedures for the molded wax pattern.

3. Pattern Assembly Logic: After the individual wax pattern pieces are created, they must be assembled onto a sprue with the proper gating attachments. In this stage of the process, sprue and ingate sizes and positions must be considered in association with the width of the freezing range if an alloy is to be cast. The experimental results of Osinskii et al.[28] suggest the following guidelines:

> "Narrow-interval alloys require heat accumulation around the sprue and ingates. Sound castings can be made by accumulating surplus molten metal ahead of the solidification front. In this case, the optimum conditions correspond to wide-section ingates and sprues, mold preheating, the use of short sprues and some reduction in the relative rate of molten metal supply to the mold cavities.
>
> Intricate castings in wide-interval alloys must be made under conditions which will prevent excessive heat accumulation round the gating system and mold cavities and minimize the volume of molten metal ahead of the

> solidification front. Sound metal can be ensured by directional solidification. In this case, mold preheating, commensurate metal weights and sprue lengths, helical mold assemblies round the sprue and normal ingate and sprue cross sections should lead to a certain 'freezing' action, while rapid mold cavity filling with metal in this condition should lead to layerwise solidification."

4. Investing and Stuccoing: Based upon the research findings obtained by Jessen et al.,[27] a slip consisting of zircon flour mixed with 30% colloidal silica binder, colloidal silica as a wetting agent, and zircon sand could be used successfully to build up the investment shell molds for pure uranium. For uranium alloys, an investment stucco of yttria may be required to handle the higher melting temperatures. Some details that need to be considered during this stage are the powder particle size fraction of the flour used to make the slurry or slip as well as those of the zircon sands used in the various stuccoing sequences and the drying times between dippings. This stage of the process can be enhanced by the incorporation of robots which are currently used extensively in the investment casting industry as mentioned previously. With proper attention to climate control in conjunction with automation, reproducible investment shells may be produced economically.

5. Dewaxing: In this phase, the selection of a dewaxing temperature is needed. Also, if the wax will be recycled, a means of collecting the wax must be devised. Another factor which should be determined is the proportion of used wax to be mixed with new wax for subsequent pattern making operations.

6. Firing: After dewaxing, the investment shell mold must be fired to achieve the necessary strength to withstand the pouring of molten metal into the mold. This requires the determination of a proper firing temperature and time.

7. Pouring: This step of the process requires the determination or consideration of several factors, namely: the mold pre-heat temperature and time, the mechanism by which molds are transferred into a furnace for casting, the subsequent creation of a vacuum within the furnace, and the temperature at which the molten metal is to be poured. Another factor to be considered is the addition of vertical centrifugation to the casting process. The action of centrifugal force has been shown to improve the casting density and mechanical properties.[28] If vertical centrifugation were desirable, the mechanics of the process would necessitate some modification to the mold fixturing equipment within the furnace so that the high rotational speeds associated with this technique could be achieved.

8. Knockout: After the casting operation is completed, the finished parts with attached ingates and sprues are removed from the investment shell by simply breaking the shell. Some thought should be given to devising a mold reclamation program. By collecting spent investment casting molds and using the caustic leaching and sizing technique developed by the Bureau of Mines, the zircon in the molds may be recovered and recycled for use in future molds. This not only reduces the amount of waste produced as a result of casting uranium or uranium alloys, but also helps to reduce the cost of the process by eliminating the need to purchase fresh zircon for each mold investing and stuccoing cycle.

9. Finishing and Inspection: The need or extent of final finish machining of the investment cast part may be eliminated or reduced. This would depend upon the surface quality achieved versus the surface finish required of the part for its intended application. However, in general less final machining will be required due to the near net shape capability of the investment casting technique. This, in turn, also generates a cost saving as well as a reduction in the amount of machining waste generated.

10. Waste Generation Considerations: Whether or not the investment casting technique could lead to actual waste minimization is unclear at this time. It could very well be that the amount of primary metallic uranium waste is significantly reduced while at the same time the amounts of secondary and tertiary wastes are dramatically increased. In order to determine the true impact of investment casting upon waste generation and minimization, an experimental feasibility study and associated cost-benefit analysis would need to be undertaken to address the following barrage of questions.

If the investment mold zircon becomes contaminated with uranium, where does the uranium go during a caustic leaching and sizing zircon recycling operation? Does it remain with the zircon or does it contaminate the fluids used for leaching and sizing, thus creating hazardous wastes or mixed (hazardous and radioactive) wastes? If the uranium stays with the zircon, can the contaminated zircon be reused for making new molds or does the presence of the uranium in the zircon cause mold problems (e.g. heat transfer, strength)? If uranium-contaminated zircon is reusable for mold materials, can the pattern waxes become contaminated when they are melted out of the molds? If the wax does become contaminated, can it be reused without negatively affecting the quality of subsequent wax patterns made from it? If contaminated wax does not affect pattern quality, will the contaminated wax then contaminate the wax molding machine dies, die lubricants, wax pattern cleaning and degreasing agents? If so, what is the extent of hazardous or mixed waste generation? If contaminated wax is not suitable for reuse in pattern making, can the uranium be separated from the wax so that both the wax and the uranium can be reclaimed? If the wax then is reusable, what is the quality of the uranium? Did it experience unsatisfactory contamination from H, C, N or O making it unsuitable for recycle into melt stock? In the resulting system flow chart, what is the impact of the various process steps on worker exposure to radioactive materials and/or wastes?

Once all of the waste generation issues are resolved, the determination of the best combination of material and casting parameters involved in the investment casting process should be addressed. To achieve the best casting soundness and mechanical properties could be a lengthy and costly process if an entirely experimental approach were selected. A more cost-effective and time-effective approach would be to use computer modeling of the casting process (considering such factors as material properties, fluid flow and heat transfer) in conjunction with experimentation. By using such an approach, the potential benefits of applying investment casting (or investment casting in conjunction with vertical centrifugation) to uranium or uranium alloys could be realized by the production of near net shape parts at lower costs and with less hazardous waste generation.

VIII. ACKNOWLEDGEMENTS

The author acknowledges the Air Force Office of Scientific Research for the position of Military Research Associate in MST-6 at Los Alamos National Laboratory.

IX. REFERENCES

1. *Metals Handbook*, 9th ed., Volume 15, (ASM International, Metals Park, OH, 1988), p. 253.

2. L. Buchakjian, "New Technology for Investment Casting," *Leading Edge*, Fall 1987, pp. 32-37.

3. *A Practical Guide to Investment Casting*, Arwood Corporation, Brooklyn, New York, 1961.

4. W.E. Cromwell, "Solid Modeling by SynthaVision: A Means of Reducing Tooling and Unit Cost for Investment Castings," Bendix Kansas City Division report: BDX-613-2940, (September 1983).

5. P. Vasin and V.A. Lonzinger, "Calculating the Thermal Durability of Investment Shell Molds," *Soviet Castings Technology*, Allerton Press Inc., **2**, (1987).

6. T.R. Wright and H. C. Wagner, "Howmet Reclaims 80% of Investment Casting Materials," *Foundry Management and Technology*, **112** (2), 60-61, (May 1984).

7. K. Wiese-Nelson, "Reclaimed Investment Casting Wax Cuts Costs," *Foundry Management Technology*, **107** (7), 116-122, (7 July 1979).

8. "Microwave Energy Beams Benefits to Investment Casters," *Precision Metals*, **34** (5), 48-50, (5 May 1976).

9. E.D. Calvert, "An Investment Mold for Titanium Casting," Bureau of Mines Report of Investigations: PBB2-104662, (July 1981).

10. E.D. Calvert and H. W. Leavenworth, Jr., "Zirconium Oxide Molds for Small Molybdenum Investment Castings," Bureau of Mines Report of Investigations: PB82-202995, (March 1982).

11. C.W. Smith and T. O. Llewellyn, "Recovery of Zircon From Investment Casting Molds," United States Department of the Interior, Bureau of Mines Report of Investigations: BM-RI-8958, (1985).

12. F. Quigley and E. Deluca, "Particle Coating in Investment Casting Mold Manufacture Utilizing Solid Fluidization," Watertown Arsenal/Rodman Laboratory Memorandum Report No. RPL 13/7, (February 1959).

13. R.C. Rodgers, "Automating Material Handling," *Foundry Management and Technology*, **115**, 51-54, (July 1987).

14. J. Mathew, "Robotic Applications in Investment Casting," Technical Paper MS85-529 from Conference: Robots 9, 2-6 June 1985.

15. D.J. Farley, "Robots for More Productive Investment Casting," *Foundry Trade Journal*, **162** (3372), 536-539, (June 16, 1988).

16. T.L. Coghill and K. J. Hesing, "Making Investment Casting Moulds Automatically Without Robots," *Foundry Trade Journal*, **162** (3347), 427-428, (21 May, 1987).

17. "Rail System Speeds Blast Cleaning of Investment Castings," *Foundry*, **101** (9), 102-104, (September 1973).

18. "Waukesha's Investment Casting Plant Forecasts Future of Foundry Industry," *Modern Casting*, **73** (9), 25-27, (September 1983).

19. B. Nagler, "Revamped Robotic Process Cuts Scrap Rate by 300%," *Robotics Today*, **9** (5), 25-26, (October 87).

20. D. Twarog, "Environmental Control Assures Repeatable Shell Production," *Modern Casting*, **78** (4), 62, (April 1988).

21. J. Hockin, "How to Reduce the Cost of Investment Castings," *Precision Metal*, **30** (10), 72-74, (October 1972).

22. S.J. Walker, "Origins and Characteristics of Internal Porosity in Steel Investment Castings," *Cast Metals Research Journal*, **7** (1), 13-17, (March 1971).

23. M. Brezina and V. Kondic, "Flow Phenomena in Investment Casting," *British Foundryman*, **66** (12), 337-348, (December 1973).

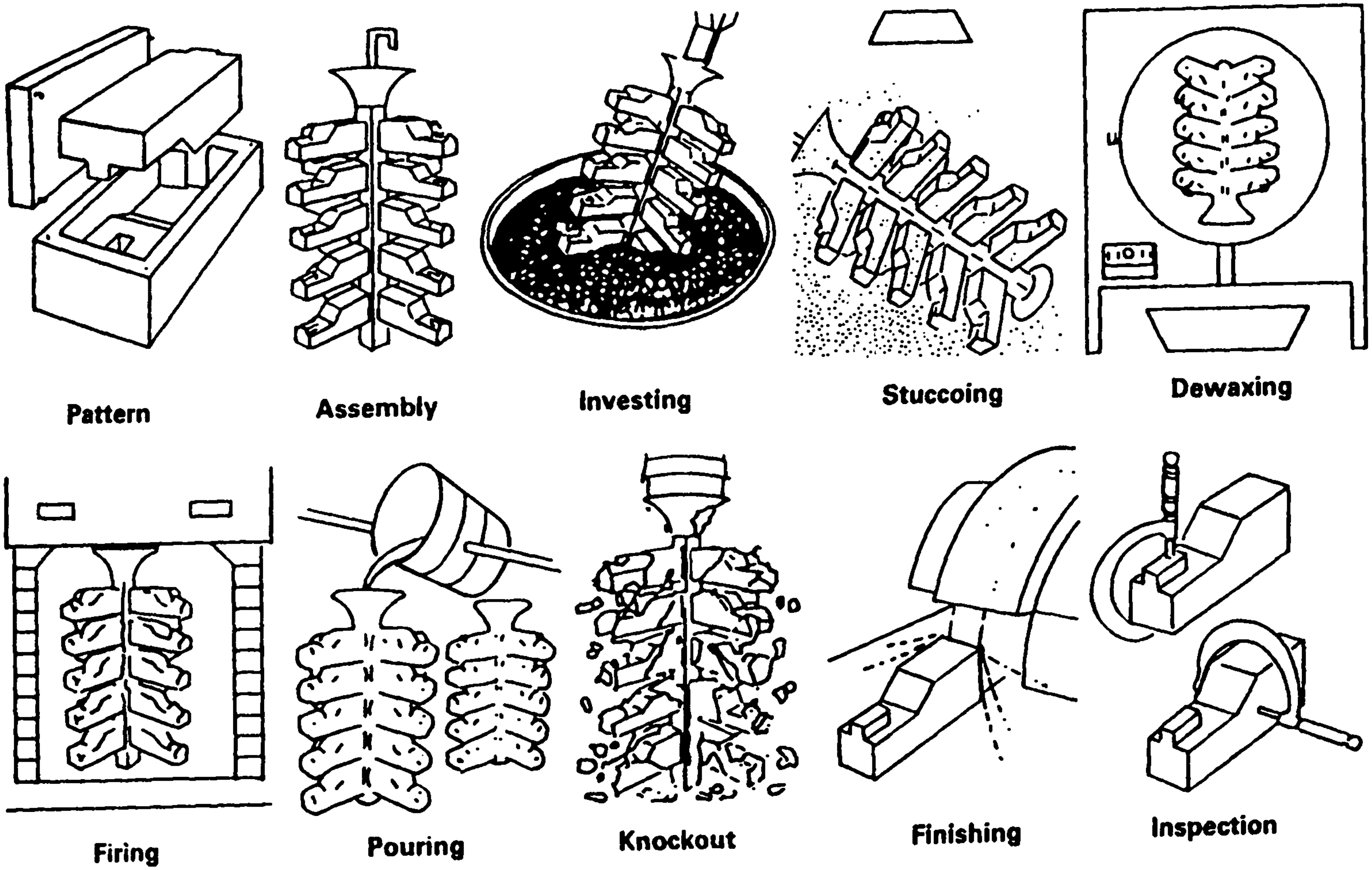
24. N. Kumar, "Causes of Dimensional Distortion in DS, Cored, Turbine Blades Produced by Investment Casting of Superalloys," Rolls-Royce Reprint: PNR90479, (17 October 1988).

25. R. Arase, S. Ohama, K. Sezake, and N. Ujiiye, "Prediction and Simulation System of Shrinkage Formation for Investment Castings," Ishikawajima-Harima Engineering Review, **26** (1), 13-17, (January 1986).

26. Army Investment Casting Industry Report, Army Materiel Command Study Team, Report Number: AD-A180-250, (April 1987).

27. N.C. Jessen, Jr., C. E. Holcombe, Jr., and A. B. Townsend, "Application of Metal Oxide Refractories for Melting and Casting Reactive Metals," in Proceedings of the Sixth International Vacuum Metallurgy Conference on Special Melting, American Vacuum Society, 381-400, (1980).

28. V.I. Osinskii, M.V. Solov'ev, and A.V. Morozov, "Soundness of Intricate Centrifugally Cast Investment-Mold Castings," (Translation) Soviet Casting Technology, Allerton Press Inc.,**7**, 50-54, (1987).



Pattern

Assembly

Investing

Stuccoing

Dewaxing

Firing

Pouring

Knockout

Finishing

Inspection

Fig. 1 Steps in the investment casting process (ref. 1).

Los Alamos
NATIONAL LABORATORY
Los Alamos, New Mexico 87545