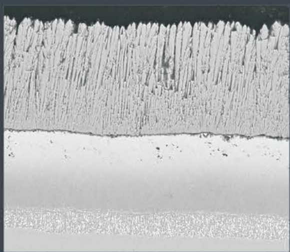
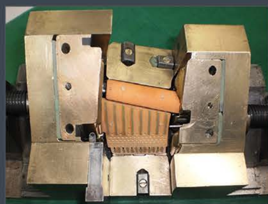
# Investment Casting: A Treasure Trove





Defence Research &
Development Organisation
Ministry of Defence, India

**AM Sriramamurthy**

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# A Treasure Trove

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**Defence Research and Development Organisation**
**Ministry of Defence, New Delhi – 110 011**
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**INVESTMENT CASTING: A TREASURE TROVE**

AM Sriramamurthy

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# Contents

# Preface

Investment casting is perhaps the oldest of casting processes dating back to 5000 BC, characterised by its ability to reproduce intricate details of the pattern made of wax. Although Indian subcontinent was an early entrant practicing this method for casting various images at Mohenja-daro (now in Pakistan), dating back to 2500 BC; it was discontinued and resurfaced in first century AD in Taxila for making gold jewellery, after a gap of about 2500 years. In the world scenario, the process was first used for value added parts in dentistry in the $19^{th}$ century. Its major unanticipated application for critical parts is its use for casting of aviation gas turbine aerofoils during the Second World War in the early 1940s for supplementing the production of wrought superalloy parts. Since then it has been associated, inextricably, with development of superalloys that went through wrought to cast, at the same time transforming itself from solid moulds to shell moulds. The success of application of this casting technique allowed increasing the strength of superalloys that cannot be forged, which marked the beginning of development of cast superalloys. The introduction of shell moulds made use of ceramic cores possible, which enabled designers to design hollow parts with complex/more efficient, internal cooling passages. Improvement in the refractoriness of the shell moulds made the shells suitable for usage even with the newly invented process of directional solidification (DS), that is used for making columnar grained as well as single crystal parts. Reduction or elimination of grain boundary strengtheners in the composition of superalloys raised their incipient melting temperature so as to allow complete solutionisation of strengthening precipitate known as gamma prime, γ', as well as their homogenisation; both allowed subsequent precipitation of well-aligned γ' , which accorded quantum jump in the creep strength of the alloy parts, thus making single crystal superalloy parts practical.

Perhaps, in the field of metallurgy there is no case of a cast part being used for such critical application as gas turbine aerofoils. The rapid progress that was seen in the development of gas turbine engine is due to the synergy between a unique alloy system that could be used up to homologous temperatures as high as 0.7–0.75 (perhaps due to coherent or nearly coherent ordered precipitate that maintains individuality even at an unusually high volume fractions of 0.65–0.70) and the investment casting technique, a unique casting technique.

Turbine entry temperature (TET), that is the highest temperature the turbine aerofoils experience, is a unique parameter that determines the efficiency of a gas turbine. And, only gamma prime strengthened nickel-base superalloys are known to withstand such high temperatures. It is therefore very difficult to imagine the state of the aviation industry in the absence of development of such alloys.

DMRL has initiated serious efforts for development of investment casting in the mid-70s to produce columnar-grained directionally solidified gas turbine aerofoil parts. Considering the long gestation periods for the development of such technologies, efforts were simultaneously initiated for the development of surface protection coatings and ceramic cores required for casting of parts with complex internal cooling passages. Efforts towards development of pattern injection dies were initiated only in the early 80s. A separate group for die design and die fabrication was formed in the mid-80s. This group could supply the requirements of casting development successfully while learning lessons through constant development of concepts, building-up of best software for design, and generating machining programmes and hardware for dimensional evaluation as well as partnering with CNC machining centres in addition to developing in-house competence. This monograph covers all the above allied technologies to achieve comprehensive self-reliance.

Since we could mature the casting technology and demonstrate it through casting of Kaveri engine parts as well as integral castings for Jet Fuel Starter that went through type certification, this technology was transferred to Hindustan Aeronautics Limited (HAL) (Koraput) as recommended by a special committee appointed by DRDO. The foundry at HAL also got type certified for all the parts for which DMRL transferred the technology.

During 1990–2006, core making technology was also matured by demonstrating it on various cores of Kaveri engine successfully using dies supplied by casters of Kaveri engine parts as well as a die procured by DMRL directly. During the same period, coating development for platinum aluminide to the specification of Kaveri engine parts was also matured and is now moving towards development of thermal barrier coating through Electron Beam Physical Vapour Deposition (EBPVD) process. Thus, DMRL has clearly achieved a greater degree of self-reliance in component fabrication technologies.

Considering the overall maturity of Investment Casting and related technologies, it was prudent to develop commercially viable technology for production of high quality superalloys to the standards demanded for casting. MIDHANI was identified to establish a 600 kg VIM furnace, and develop and demonstrate the technology by going through type certification. The alloy chosen as a model was CM247—the alloy chosen for Kaveri engine—was taken as a model for development, and MIDHANI accomplished this task successfully.

This monograph is designed to serve the objectives of the DRDO monographs published by DESIDOC. We have included conclusions summarising the main achievements at the end of each chapter and also a separate chapter on the level of indigenisation of certain major equipment and novel tools to appeal to peers and experts. This monograph will be useful to post graduates and researchers as we have presented the work done as comprehensively as possible; which also, serves as a status report as desired by Dr Malakondaiah, the then director of DMRL when monograph was initiated.

In the introductory chapter, we have included a write up on gas turbine engine with a detailed thermodynamic analysis of gas turbine thermodynamic cycle to show that efficiency of energy conversion is decided by the turbine entry temperature, i.e., the temperature of the gases exiting from burner and directly impinging on the first stage vanes. This explains the environment in which the castings being developed by DMRL have to work, and gives an appreciation of the critical role of the casting technology. This chapter also includes a brief overview of development of superalloys and investment casting process to serve as background for ease of understanding further chapters.

The second chapter on superalloys is a brief narrative, meant to give an overview, on the history of development of superalloys, the benefits of having γ' with its anomalous mechanical behaviour and mechanisms of strengthening, and influence of various alloying elements and methods of avoiding undesirable phases, and work that is going on and approaches being taken for improving working temperatures, that might benefit all working scientists in the area of investment casting.

The third chapter describes in detail the work done in DMRL in the development of ceramic mould making for investment casting and directional solidification, and casting for components, solid or internally cooled hollow castings with equiaxed grain structure through conventional casting and columnar grain or single crystal structure through directional solidification. Significance of orders of magnitude difference between ceramics of which the shell moulds are to be made and waxes and consequent need to maintain temperature of the wax, of which patterns and other parts of the clusters are made throughout the shell mould making operations to obtain moulds of high integrity, difficulties faced due to incompatibility of ethylsilicate based binder with inoculants and need to change over to colloidal silica binder, importance of filler to binder ratios, refractoriness of ceramics, control of ambience, leading us to replacing all indigenous raw materials with all imported raw materials in-addition to better control of ambience during shell making operations, and use of best of de-waxing autoclaves to produce completely crack free moulds suitable for directional solidification are presented. In addition, studies on refractoriness of various ceramic combinations and effect of some special additives that increases the refractoriness of bonding silica, and metal mould reaction, leading us to produce moulds suitable for directional solidification at much higher temperatures (that might be required for higher generation single crystal superalloys) is presented. It also includes conventional casting of individual and integral bladed aerofoil casings with grain size control, modifications of hot zone of mould heater for directional solidification for casting columnar grained or single crystal castings and mould design and optimisation of casting parameters for a number of castings. Of particular importance is the successful development of Kaveri engine castings, which are internally cooled columnar grained parts that went through type certification. The efforts for casting single crystal castings in an ongoing project has been highlighted. It also includes the simulation studies initiated with useful results that could be supported by casting studies.

The fourth chapter deals with the development of die design and die fabrication which progressed rather smoothly. This chapter begins with general principles dealing with various issues to be considered like compensation of shrinkages, parting surfaces, how the design changes with the features of the part, dealing with core design, evaluation of shrinkages and warpage, if any. Next, it moves over to design, fabrication and assembly of dies for a variety of parts and influence of specific features of the parts on the die design like vane castings and hollow parts that use ceramic cores. Also included is building of assets, both software and hardware, and their application not only in the fabrication of dies for various purposes but also in dimensional evaluation of cast parts and reverse engineering of castings.

The fifth chapter deals with development of technology for ceramic cores that took off from early 1990s in a most systematic manner. A detailed narration with justification of choice of various components and methods of all steps of processing is given. Design of dedicated tools for characterisation and processing including major tools like mixer, injection moulding machine and firing furnace as well as high temperature flexural strength evaluator are also presented.

The sixth chapter deals with development of surface protection coatings, specifically platinum aluminide equivalent to RT-22 of chromalloy specified by GTRE for their turbine engine. It also deals with scaling up to a small batch level. It also deals with recently initiated work on the application of thermal barrier coatings through electron beam physical vapour deposition (EBPVD). The presentation also includes analysis of failures reported by GTRE in which platinum aluminide coating played an active role and possible potential solution.

The seventh chapter deals with indigenisation of certain major equipment and tools and also certain equipment with novel ideas for achieving greater degree of self-reliance. Some of the major equipments indigenised are core leaching autoclave and investment casting furnace. Design and development of ceramic core injection machine, and high temperature four-point bend tester that appears to have exceeded even imported tools in consistency. A few examples of equipment involving very novel ideas which are not available in the commercial international market are also described.

The eighth chapter presents an overview of our achievements in all related technologies, extent of self-reliance in not only processes, but also in the area of major/critical equipment and successful transfer of technology and denial regime which is not in our hand. It also points out presence of self-created road blocks.

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# Acknowledgements

Firstly, I thank Dr G Malakondaiah, the then Director, DMRL, for inviting me to write this monograph on Investment Casting technology, a subject on which I spent most of my service life in DMRL. I am grateful to him for extending all facilities I needed and also for giving me the freedom to interact with many scientists. I also thank Dr Amol A Gokhale, who took over from Dr G Malakondaiah for continuing all support. For, without such a support, it could not have been possible to prepare such a comprehensive monograph. My grateful thanks are due to Dr CP Ramanarayanan, Director, GTRE, for providing me permission to interact freely with the Turbine Group; I thank Shri Ramanamurthy, of Turbine Group for many rounds of discussions, providing all necessary literature and critical review and comments on my write-up on gas turbine engines in the introductory chapter. My special thanks are due to Dr M Vijayakumar for extending all the help in managing this project, and for providing detailed information on ceramic development programme for which he is solely responsible – a subject on which we had many discussions in the initial days of his induction into this subject in early 90s. I thank Shri Niranjan Das and Shri Satyapal Singh, the two major pillars of Investment Casting Group taking the development process to greater heights, for providing all necessary information including application of simulation of casting process. I thank Shri N Hazari for undertaking literature search in addition to providing me all the literature he has, for preparing the chapter on 'Superalloy- a narrative'. My thanks are due to Shri MAH Baig and Shri R Pradyumna, the two senior scientists of Die Design and Die Making Group for several discussions in spite of their intense involvement with design and fabrication of a very complex die urgently required for an important project. I also thank Shri Sankarasubramanian of Modelling & Simulation Group; Shri S Sridhar, Shri Alok Singh Chauhan and Shri Nandam Srinivas of Die Design Group; Shri Venkat and Shri Kumar Sourab of Investment Casting Group; Shri Abhoy Kumar and Shri RD Sharma of Ceramics Group; Smt Gokul Lakshmi of Coatings Group; and many other scientists who have whole-heartedly given their inputs for the preparation of various chapters. My thanks are also due to Dr DK Das for providing me all internal reports that comprised information on the work done in the development of the platinum aluminide coating process and its characterisation and the several discussions I had with him. Finally, I thank all the personnel of Director Secretariat, DMRL for readily extending their services.

Despite the fact that I have acknowledged a few scientists who contributed to the preparation of this monograph, I would also like to mention that a large number of officers have contributed to the successful development of this comprehensive technology that took more than three decades to reach the current status. Dr VS Arunachalam, former Director/DMRL and subsequently SA to RM & DG/DRDO who had initiated the programme and driven it with passion through out his association with DRDO should occupy the pride of place. During the initial years of his service at DMRL, he took special interest in this work. Knowing that India is one of the early entrants practising this process for casting temples idols in South India, he extensively toured South Indian temples to identify such idols. Temples to Turbines has become his passionate subject of oration. We dedicate this monograph as a tribute to this legend. Besides him, there are: Dr ML Bhatia, Dr SN Tewari, Dr R Sivakumar, Dr D Banerjee former Director/DMRL and later CC(R&D)(AMS), (late) RS Raju, (late) M Hema Reddy, Shri N Swamy, and Shri AV Narasimham, who have also contributed immensely at different levels to the progress of this technology. It is but natural that in a programme like this spread over a few generation of scientists, it is difficult to mention all the names. I gratefully acknowledge all their contributions.

Coming to this monograph, I thank Shri Gopal Bhushan, Director, DESIDOC, for readily extending all the support that the monographs division needed in bringing out this monograph. My special thanks are due to Smt Anitha Saravanan, Head, Monographs division, who took every step needed considering that this document covers science and technology in several areas of specialisation. Finally, I thank Smt Gunjan Bakshi, Editorial Assistant, for her support including redrawing large number of figures that were not clear enough for publication.

AM Sriramamurthy

## List of Acronyms

| | |
|---|---|
| ADA | Aeronautical Development Agency |
| APB | Anti-phase Domain Boundary |
| ARCI | Advanced Research Centre for Power Metallurgy and New Materials |
| ARDB | Aeronautics Research and Development Board |
| ASL | Advanced Systems Laboratory |
| BARC | Bhabha Atomic Research Centre |
| BHEL | Bharat Heavy Electricals Ltd |
| BPR | Bypass Ratio |
| CBVC | Critical Binder Volume Concentration |
| CCM | Coordinate Measuring Machine |
| CFD | Computational Fluid Dynamics |
| CIM | Ceramic Injection Moulding |
| CIP | Cold Isostatic Pressing |
| CIPET | Central Institute of Plastics Engineering and Technology |
| CITD | Central Institute of Tool Design |
| CMTI | Central Machine Tool India |
| CTAB | Cetyl Trimethyl Ammonium Bromide |
| CVD | Chemical Vapour Deposition |
| DC | Die Clamping |
| DDF | Die Design and Fabrication |
| DDG | Die Design Group |
| DGOF | Director General of Ordnance Factories |
| DMRL | Defence Metallurgical Research Laboratory |
| DPT | Die Penetrant Testing |
| DRDO | Defence Research and Development Organisation |
| DRDL | Defence Research and Development Laboratory |

| | |
|---|---|
| DS | Directional Solidification |
| EBPVD | Electron Beam Physical Vapour Deposition |
| EDM | Electrical Discharge Machining |
| EPMA | Electron Probe Micro Analyses |
| ETC | Enabling Technology Center |
| FCC | Face Centered Cubic |
| FDM | Finite Difference Method |
| FEM | Finite Element Method |
| FPI | Fluorescent Dye Penetrant Inspection |
| FPTR | Free Power Turbine Rotor |
| FPTS | Free Power Turbine Stator |
| GGTR | Gas Generator Turbine Rotor |
| GGTS | Gas Generator Turbine Stator |
| GTRE | Gas Turbine Research Establishment |
| HAL | Hindustan Aeronautics Ltd |
| HHPCIM | Horizontal High Pressure Ceramic Injection Moulding |
| HHV | Hind High Vacuum |
| HIP | Hot Isostatic Pressing |
| HMOR | Hot Modulus of Rupture |
| HPT | High Pressure Turbine |
| HPLC | High Pressure Leaching Chamber |
| HRS | High Rate Soildifiction |
| IGCAR | Indira Gandhi Centre for Atomic Research |
| IGT | Industrial Gas Turbine |
| IM | Injection Moulding |
| IRE | Indian Rare Earths |
| JFS | Jet Fuel Stator/Starter |
| LBBC | Lee and Bardford Boilerclave Company |
| LCA | Light Combat Aircraft |
| LE | Leading Edge |
| LMC | Liquid Metal Cooling |
| LPT | Low Pressure Turbine |
| LPTB | Low Pressure Turbine Blade |
| LPTV | Low Pressure Turbine Vane |
| LVDT | Linear Variable Differential Transformer |
| MD | Metal-d Levels |

| | |
|---|---|
| MOR | Modulus of Rupture |
| MTO | Motors Transport Officer |
| NAL | National Aerospace Laboratories |
| NDT | Non-destructive Testing |
| NSTL | Naval Science & Technology Laboratory |
| NTPC | National Thermal Power Corporation |
| NURBS | Non-uniform Rational B-spline and Surfaces |
| ODS | Oxide Dispersion Strengthened |
| PID | Proportional Integral Derivative |
| PIM | Powder Injection Moulding |
| PM | Powder Metallurgical |
| POP | Plaster of Paris |
| PSU | Public Sector Undertaking |
| PTAE | Pilotless Target Aircraft Engine |
| PVA | Polyvinyl Acetate/Alcohol |
| RH | Relative Humidity |
| SEM | Scanning Electron Microscope |
| SFC | Specific Fuel Consumption |
| SC | Single Crystal |
| TBC | Thermal Barrier Coating |
| TCP | Topologically Closed Packed |
| TE | Trailing Edge |
| TEM | Transmission Electron Microscope |
| TET | Turbine Entry Temperature |
| TGA | Thermo Gravimetric Analysis |
| TGO | Thermally Grown Oxide |
| TOT | Transfer to Technology |
| UFA | Ultrafine Alumina |
| UTS | Ultimate Tensile Stress |
| VCD | Vane Core Die |
| VIM | Vacuum Induction Melting |
| YS | Yield Stress |

# CHAPTER 1

# Introduction

## 1.1 DEFENCE METALLURGICAL RESEARCH LABORATORY

The Defence Metallurgical Research Laboratory (DMRL) has taken up indigenous development of hot end components of gas turbine engines, including all subsidiary technologies, in a very comprehensive way, starting from the mid-seventies, so as to support the development of gas turbine engines in our sister laboratory, Gas Turbine Research Establishment (GTRE), Bengaluru. Such support to our sister laboratories is a part of our business mandate as summarised below. In pursuit of achieving total self-reliance in this, DMRL has been successful not only in mastering the difficult technologies involved such as casting, die design and fabrication, ceramic core making, surface protection coatings including thermal barrier ceramic coatings, etc., but also in indigenising many of the major facilities.

### 1.1.1 Business Mandate of DMRL

- Formulate and execute scientific and technological programmes in the area of metallurgy and materials science relevant to national security.
- Transform the laboratory scale technology into production capability to meet the requirement of the Armed Forces.
- Provide metallurgical and materials science research and development inputs to the development programmes of other laboratories under Defence Research and Development Organisation (DRDO).
- Render scientific and technological expertise in the area of metallurgy and materials science to ordnance factories, public sector units, and industries of the country to achieve self-reliance.
- Carry out failure analysis of metallurgical components for defence services and system laboratories to help avoid recurrence in the future.
- Create and continuously upgrade competence among DRDO scientists in specialised and frontal areas of metallurgy and materials science.

- Generate intellectual property in the form of patents and copyrights.
- Render advice on the technological and intellectual property aspects in the area of metallurgy and materials science in DRDO.
- Render scientific and technological expertise in the area of metallurgy and materials science to other national laboratories under Department of Space, Department of Atomic Energy, and Department of Science and Technology, to support their programmes of national importance.
- Provide spin-off technologies developed by DMRL for civilian use.
- Support any other activity assigned to and accepted by DRDO through understanding or agreements with any other ministry, department and agency of the Government of India whose activities have a bearing on the scientific and technological aspects of national security.

## 1.2 GAS TURBINE ENGINES

### 1.2.1 Introduction

DMRL has been developing the most important/critical components namely, the turbine aerofoil components of gas turbine engines that power (i) propulsion of various aircrafts, (ii) land-based power generators, (iii) propulsion of ships, etc. Hence, it is appropriate for us to understand how a turbine engine works and why and how the performance of the engine is decided.

Gas turbine engines are said to be far more efficient than the auto piston engines. Historically, the Wright brothers used piston engines when they flew their aircraft successfully in 1905; these engines have continued to power aircrafts since then. The gas turbine engine was successfully bench-tested by Frank Whittle in 1937, and Hans von Ohain flew an aircraft powered by a gas turbine engine around 1940.

It appears that the gas turbine itself is not new. Chester T. Sims, in an article in 1984[1] traces the concept of gas turbine to 1648 AD when Bishop Gibbons described a gas turbine that could be used for doing household chores by realising the power of rising hot air in the chimney of a fire-place. This then led thermodynamically to the Brayton cycle, a basic tenet that holds that higher use temperature results in more efficient operation. The Brayton concept was applied to rotating engines, specifically advanced steam engines in the 19$^{th}$ Century. In 1923, Aegidius Elling designed a commercially successful land-based gas turbine engine for power generation. In the early years of the last century, advances in aerodynamic theory brought about radical changes in the thinking of designers in England, Germany and Italy.

- It was realised that turbulent drag wasted two-thirds of the power applied to a conventionally driven aircraft.

## DRDO Monographs/Special Publication Series

**About the Monograph**

Modern aircrafts operate on high efficiency gas turbine engines. Making the turbine engine components such as blades and vanes, which operate at high temperatures under very demanding conditions, is more of an art, restricted only to a few advanced technology companies in the world. Investment Casting process technology forms the backbone of producing such components on an industrial scale. This technology demands expertise in a variety of engineering fields, from superalloy metallurgy and high temperature ceramics to complex tool design and fabrication, surface coatings, testing and quality control, etc. This monograph attempts to provide a comprehensive description of this highly specialised technology developed indigenously in Defence Metallurgical Research Laboratory (DMRL), through the research efforts of numerous scientists over a period of three decades. An exposition of the principles underlying various processes for casting a variety of gas turbine engine parts, with equiaxed, columnar grained, single crystal structure and integral bladed (blisk) castings, is also included for the benefit of interested students and researchers. The monograph also covers some of the innovations that led to the indigenous design and fabrication of major/critical tools and equipments, thus making the technologies developed comprehensive and helping achieve a high level of self-reliance.

**About the Author**

Dr AM Sriramamurthy was born in 1947 in Machilipatnam, a historic port town in Krishna district of Andhra Pradesh. He joined DMRL after completing his BE and ME in metallurgy from the Indian Institute of Science, Bangaluru in 1972. He worked throughout his career on the development of investment casting technology for making superalloy aerofoil castings for gas turbines. He has distinguished himself as one of the foremost experts in the country in this area. Apart from this, his research interests and expertise span a wide range of areas in optics, diffraction, mechanics, mechanical/deformation behaviour of materials, structure property correlation, and thermodynamics. Dr Sriramamurthy superannuated from DRDO in 2007 after serving as Director of DMRL from 2003 to 2007.

"...*madhuchchhishtavidhana* ... He has come forward to enumerate the whole story.
...describing the entire pursuit, including the underlying theories.
...the story of the Indian Investment Casting is now complete."

... VS Arunachalam

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