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# Indian investment casting from ancient to aerospace

**Dr. Niranjan Das**
**DMRL**
**(Defence Metallurgical Research Laboratory)**

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# Indian investment casting from ancient to aerospace

**Niranjan Das**

**Defence Metallurgical Research Laboratory, Hyderabad**

## Abstract

The history of investment (lost-wax) casting dates back to 3500 BC with the bronze statue of dancing girl found in Harappan Civilization. Bronze images of Lord Buddha at Amaravati and Lord Rama and Kartikeya in Guntur district of AP state in India were also investment cast idols made in the 3rd and 4th centuries AD.[1] All these idols and many more bronze icons recovered from Saranath, Sirpur, Akota, Vasantagadh, Chhatarhi, Barmer and Chambi, used natural bee-wax for patterns, ant-hill clay and river-bed sand for the moulds and manually operated bellows for stoking furnaces. Engineering production of investment cast turbine blades and vanes began in India during 1960 at HAL, Koraput for MIG aircrafts. Many investment casting companies also manufactured spare parts for textile, automobile and other industries all over India. Defence Metallurgical Research Laboratory (DMRL) of India began scientific research in vacuum investment casting during 1970s. Efforts were made towards directional solidification (DS) technology in this laboratory during early 1980s. The shell molds developed were satisfactory up to 1450°C processing. Die design and precision casting capability along with more refractory shell molding and ceramic core making for thin walled aerofoil having serpentine channels were established through a number of research projects subsequently. Several engine sets of individual aerofoil parts, integral rotors and stator rings were made and a novel technique was established for columnar grained blades along with fine grained hub in a single casting step. DMRL is now developing advanced single crystal blades out of new generation superalloys with superior metallurgical quality, yield and engine performance.

## 1. Introduction

Investment casting is a process of shaping metals where ceramic mold materials are invested layer by layer around an expendable wax replica of desired article; the replica is then replaced with molten metal that solidifies in the shape of the desired article. This process is as ancient as the Harappan Civilization in 3500BC where, the bronze casting of a dancing girl (fig.1) was found [1]. Archaeologist have established that the bronze images of Lord Buddha at Amaravati and Lord Rama and Kartikeya in the Guntur district of India were investment cast during the 3rd and 4th centuries AD [2]. All these and many more bronze icons recovered from several places in India such as Saranath, Sirpur, Akota, Vasantagadh, Chhatarhi, Barmer and Chambi used natural bee-wax for patterns, clay for the moulds and manually operated bellows for stoking furnaces. Fine details with precision and quality had been realized in these castings (fig-2) [3] not by any six sigma approach for profit but by sincere spiritual practices and seer devotion to Almighty. Engineering production of investment cast turbine blades and vanes for MIG aircrafts began in India during 1960s at HAL, Koraput.

Fig. 1 Harappan dancing girl, 3500BC.

Fig. 2 Siva, Parvati, & Nataraj of 12 century AD.

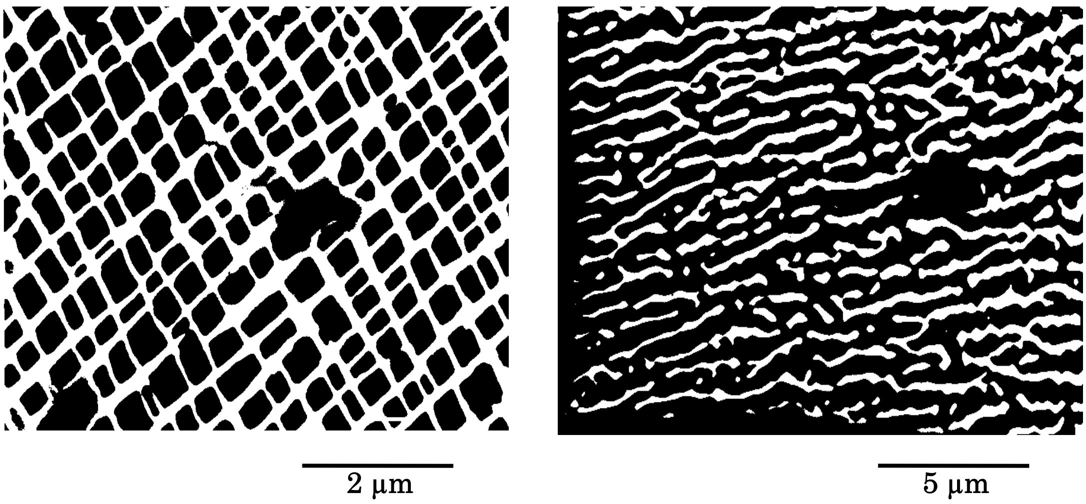
Many investment casting companies also manufactured spare parts for textile, transport, medical implants and other industries all over India such as IPCL in Bhabnagar, Unideritend in Pune, Texmo in Coimbatore. Techno-scientific research on vacuum investment casting began in 1970s at DMRL. Efforts towards directional solidification (DS) technology were made during early 1980s. The shell mold developed was satisfactory only up to 1450°C processing. Die design and precision casting capability along with more refractory shell and ceramic core making for thin walled complex aerofoil parts having serpentine channels were established here through a number of research projects subsequently. DMRL has set up an Enabling Technology Center (ETC) in the year 2002 to transform its laboratory scale gas turbine airfoil casting know-how into production technology. Several engine sets of individual aerofoil parts, integral rotors and stator rings were made in ETC on a pilot plant scale and a novel technique was established for columnar grained blades along with fine grained hub in a single casting step. This combination of better creep resistant DS blades together with fatigue resistant fine grains in hub cost effectively promises enhanced engine performance and life. DMRL is transferring these types of components casting technology to industries through hands on training for mass production and civilian applications. Development of materials and component technology for gas turbine aero-engines has been largely driven by military urge. Increasing demands for higher engine specific thrust and fuel efficiency have pushed engine operating temperatures and stresses progressively higher. Desired level of engine performance and life calls for excellent combination of high temperature strength, ductility, resistance to creep, oxidation, hot corrosion, fatigue, thermal cycling together with efficient cooling arrangement in the turbine blades and vanes. DMRL is now developing advanced single crystal blades out of its own new generation superalloys with superior metallurgical quality, yield and engine performance. This paper describes the efforts made at DMRL to meet these challenges starting from raw-materials to design and manufacture of various processing tools and innovative casting technology developments.

## 2. Raw-materials

Raw-materials for investment casting of traditional art pieces used to be bronze metal, bee-wax for pattern, clay and river bed sand in various grits for mold. Turbine blades and vanes processing however requires carefully engineered pattern wax, more refractory and chemically inert ceramic shell materials and good vacuum in order to pour reactive elements containing molten superalloys above 1500°C. Cast Ni-base super alloys with its

FCC (γ) matrix and ordered FCC (γ′) coherent precipitates have proved to be the right candidate for challenging combination of engineering properties since the last half century. The γ′ phase is stable up to temperature well above 1000°C (close to 1200°C for recent alloys) and can directionally coarsen as can be seen in figure-3 from cubic (a) to rafts (b) under engine operating conditions and enhance creep resistance. Use of these alloys extends to the highest homologous temperature of any common alloy system and they currently comprise over 50% of the weight of advanced aircraft engines. Turbine entry temperature (TET) has been improved by about 500°C since the induction of first turbojet to aerospace. About 250°C of this improvement is due to more efficient serpentine and film cooling and about 100°C is due to the use of advanced thermal barrier ceramic coatings on platform and full airfoil. The balance 30% is due to improved super alloys and advanced casting processes [4]. Figure-4 shows chronological development of various superalloys over the last 50 years. DMRL has also developed its own superalloys to cast state-of-the-art DS/SC turbine blades and vanes incorporating serpentine cooling channels[5]. It has developed the third generation single crystal alloy DMS4 and its DS derivative alloy DMD4, which offer nearly 100°C metal temperature advantage over the currently imported turbine aerofoil material for indigenous aero-engine development program and secured US patents [6],[7].

Significant improvement in shell mold quality could be realized to avoid mold cracking, hot tear, upper cast porosity and aerofoil distortion employing locally available ceramics such as fused silica, alumina, zircon and mullite powder and sand in various particle size distributions. India has vast natural reserves of these raw-materials. Quality materials suitable for DS processing however is in limited supply. Setting up of processing plants in India for such materials requires substantial rise in domestic demand from investment casting foundries.




(a) (b)

Fig. 3 (a): Cubic γ′ precipitates of superalloy DMD4, aged at 1150°C after solution treated at 1330°C; (b): Rafted γ′ structure in creep ruptured superalloy DMD4.

### 3. Casting superalloys into turbine airfoil parts

Lost wax investment molding followed by vacuum induction melting (VIM) and casting has been the only industrial means of producing turbine airfoil parts efficiently because of its ability to cast high temperature super alloys (which are otherwise not workable) into complex aerodynamic shape with better than 0.1mm dimensional tolerance. Here, a wax pattern (replica of required cast part) is made around which alternate layers of ceramic slurry and sand is built repeatedly like the shell of a snail. The wax is then removed (de-waxed) from the shell mold into which vacuum induction melted metal is poured to solidify in the shape of the mold cavity. Hollow castings are produced with internal cooling channels by incorporating ceramic core replica of desired cooling channels within the wax pattern. The desired cast part is thus realized by removing the ceramic mold and the core. This process has gradually evolved to its present level of engineering marvel through a number of materials and process innovations. The key factors for the success of this technology in the chronology of its process steps are:

Design and fabrication of various processing tools

Ceramic cores technology

Investment shell molding technology

Vacuum casting techniques and engineering

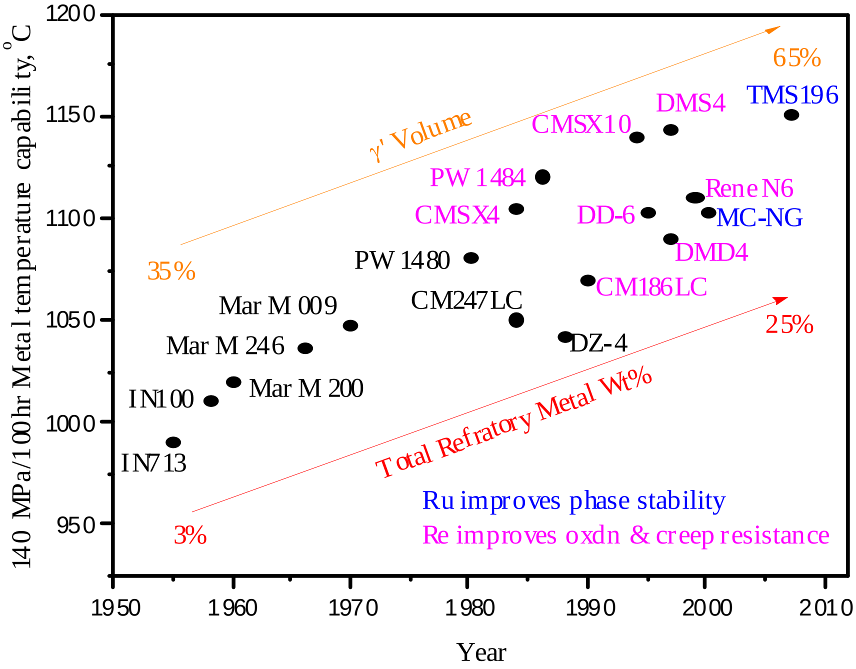



Fig. 4: Chronological development of cast Ni-base superalloys

### 3.1 Design and fabrication of various processing tools

It is the first critical step required for successful production of modern gas turbine airfoil parts wherein all the knowledge bases gathered in the field of wax and ceramic injection molding, slip casting, vacuum investment precision casting and post casting operations are pumped into computer aided design and machining of efficient, flawless and durable dies, fixtures and gauges to consistently provide quality ceramic cores, wax patterns and finally the finished cast parts in large numbers. Various allowances are built into the injection molding dies of cores and wax patterns to cater for processing shrinkages and distortions at various steps such as core injection, pattern injection, shell mold firing, molten alloy freezing and solid metal contraction depending upon the size, geometry and complexities of the casting in hand. The number of die, fixture or gauge elements and their geometry are modeled according to geometry and datum defined in the casting drawing. The size and location of injection hole, runners and vents in the die are dictated by the shape and volume of the casting. A number of extra features are often built into and around the core and casting such as tie bars, core prints, DS/SC starters, feeders, risers which are either trimmed or tolerated in the core and casting or brazed after casting depending upon geometrical complexities and aerodynamic necessities. The geometry of the component being twisted aerofoil shape, advanced Computer Aided Design and Computer Aided Manufacturing (CAD/CAM) systems are used for generating 3D models of the casting. Shrinkage and distortion behavior of the cast metal during cooling process is estimated as per size, shape and complexity of the component and imposed on the CAD model. The CAD model is further split along parting lines as per the die configuration and CAD models of die inserts are developed and Computer Numerical Control (CNC) based part programs are generated for machining the die. The machined die blocks are qualified through CMM inspection and assembled for pattern injection. Trial injections are carried out and the patterns are inspected.

The flow chart of Fig. 5 shows the sequence of steps involved in tooling development for wax patterns. The turbine blade is of sculpted shape and hence the definition of its geometry is based on a series of closed aerofoil curves twisted and placed one over the other on an imaginary axis called the "stacking axis" as shown in Fig. 6. These nominal profiles have leading and trailing edges, connected by smooth flow curves conducive for turbulence-free flow of hot gases. These curves or "splines" have stringent dimensional requirements. The profile of the measured curve on a casting has to be within tenths of a millimeter from the nominal. The relative twist of the profile and its horizontal and vertical displacement with respect to stacking axis, are stringently specified. In-house capability has also been established to reverse engineer any turbine part in the absence of proper drawing right from digitizing the blade geometry.

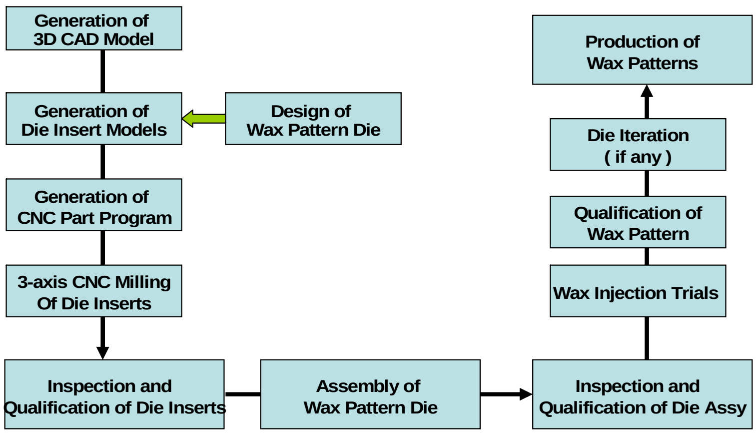



Fig.5: Wax pattern dies development flow chart

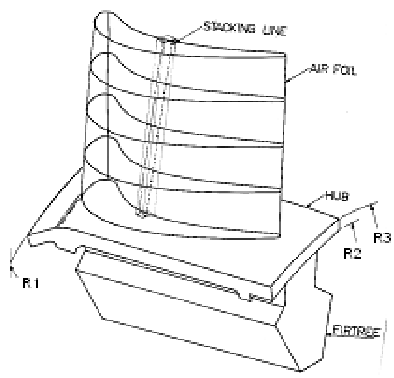



Fig. 6 Definition of Aerofoil Geometry

### 3.1.1 Facilities for tooling development

A number of facilities for CAD work and dimensional inspection have been established in DMRL in order to develop and prove injection molding dies and other tools as detailed below:

(1) CAD/CAM Facility:

It has a wide range of work stations and CAD/CAM software such as CADDS 4X/5, CATIA V4, Pro/Engineer Wildfire and CIMATRON E with advanced NURBS based surface modeling capability along with 3/5 axis CNC part program development capability to do:

- Component Modeling for Wax Pattern as well as ceramic core geometry
- Identification of split lines and die blocks modeling
- Die assembly modeling and simulation
- Generation of CNC part programs for machining
- Analysis of CMM inspection data

(2) Rapid Prototyping Facility:

It is a Fused Deposition Modeling (FDM) based Stratasys FDM 3000 facility exclusively used for generation of prototypes in ABS plastic or IC wax for:

- Verification of component modeling
- Confirmation of split methodology for dies
- Validation of new designs for fixtures
- Development of soft dies for wax pattern as well as ceramic core dies

(3) Optical Inspection Facility:

The optical inspection facility consists of the following equipment:

- Microtecnica Optical Profile Projector Model Cyclop-1, with 1000 mm screen having both diascopic and episcopic projection and measurement facility, with edge detection.
- CCD Camera based Video Measuring Microscope

(4) CMM Inspection Facility:

Coordinate Measuring Machines (CMMs) having touch probe measurement from Leitz and LK with specialized turbine blade measurement software package are used for inspection and qualification of aerofoil dies and castings. Volumetric accuracy of these machines is of the order of 1.5 – 2.5 microns. We also have a LDI make twin sensor line scanning Laser CMM facility installed specifically for measurement of ceramic cores at both green and fired stages. This machine has dimensional accuracy of 25 microns, with measurement of data up to 14,700 points/sec. The voluminous data generated by the system is extremely useful in qualifying every part of a component, unlike touch probe CMMs where qualification is based on sectional measurements.

### 3.2 Ceramic Cores Technology

Fabrication of ceramics to a complex and intricate shaped component, conforming to stringent dimensional requirements, is made possible by the process of Ceramic Injection Molding (CIM). In CIM, the ceramic powder is mixed with an organic polymeric binder in appropriate proportions under heat and shear to form a homogeneous, injection moldable feedstock. This mix is then injection molded into the desired shape using specially designed dies and suitable injection machines. The organic binder in the component is subsequently removed, and the green body sintered carefully so as to retain the shape. This required building up of expertise in diverse areas such as (A) Modelling of complex and intricate shaped core component, and Design & fabrication of dies for injection moulding; (B) Building up processing equipment required for (in) intimate mixing of ceramic powders with the organic binders to make the ceramic feedstock material, (ii) injection moulding of highly loaded ceramic feedstock, and (iii) de-binder & sintering of the injection moulded components; (C) Establishing processing methodologies and optimization of process parameters to get defect-free components and evaluation of cores through casting trials; (D) Dimensional Inspection of cores, as well as dies to tight tolerances.

#### 3.2.1 Ceramic Injection Molding

Fused silica based compositions containing small amounts of alumina, zirconia and titania form the material of choice for making ceramic cores [(8),(9)]. Surfactants like CTAB are also incorporated at this stage to improve the powder rheology. A combination of powders of different sizes that gives a tap density of ~60% is used. Organic polymeric binders, which are viscous fluids in molten condition, are blended with these powders so as to facilitate the powder particles to flow into the die cavity, fill and pack homogeneously. The binder also helps hold the particulate structure in the desired shape until it is removed completely during the de-binder step. The binder is so chosen as to ensure that it provides good rheology to the mix, and yet, it can be removed easily once molding is done. DMRL had to design and built its ceramic injection machines for the first time within the country as shown in Fig. 7 since there was embargo against import.

*Original data is broken!!*

Fig7 Indigenous CIM machine and the typical ceramic cores made using the same.

The machine has been used to injection mould a variety of cores that are further processed successfully to get defect-free sintered components. Success of the CIM process critically depends on the injection molding step. A number of process parameters such as the temperature of the mix, the speed of injection, hold pressures and times, die temperature, etc. need to be optimized and closely controlled, as the interplay of these parameters during the injection molding can lead to a variety of defects such as incomplete filling, weld lines, shrinkage cracks, voids, cracks, segregated regions, etc.

#### 3.2.2 Removal of binders

After injection molding, binders must be removed. Depending on the type of binders used, de-binder step can be accomplished by a number of carefully controlled means involving solvent extraction, catalytic de-polymerization or thermal degradation. Thermal means is more prevalent, as it is more convenient to carry out the de-binder step and the subsequent sintering step in the same furnace. The furnaces must be specially tailored to meet these specific requirements. Provision for good gas circulation within the furnace, and disposal of binder burnout gases downstream are also required to be planned. In the first stage of the heating cycle, the binder softens initially well before the degradation temperatures are reached. This softening can lead to shape distortion, or even collapse of the component as shown in fig. 8. Also, once the binder is removed, the molded part is essentially a highly delicate, porous body; in this condition, the integrity of the part is maintained by some binder residues and mechanical interlocking of particles. In most cases therefore, it becomes necessary to support the parts either by way of embedding them in a free flowing, non-reactive powder medium, or a fully supporting porous ceramic block. Such a support minimizes the component distortion during the binder softening, as well as during the period between the binder burnout and start of sintering. De-binder schedule is best prepared by studying the thermal degradation of the feedstock by TGA.

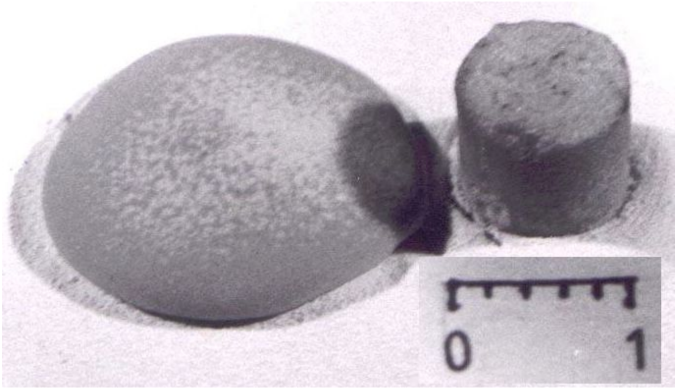



Fig.8 Shape distortion and collapse of CIM part during de-bindering

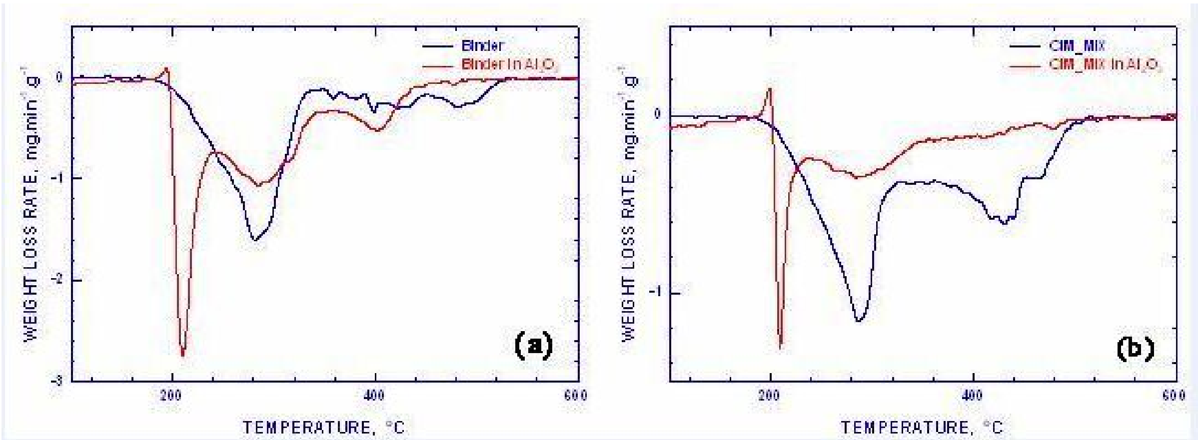



Fig.9 Thermal degradation behavior of binder through TGA (thermogravimetric analysis)

Fig. 9 shows the results of such a study. In the case of the binder alone, the degradation occurs over a very broad range of temperatures, starting from about 200°C, and peaking slowly around 280°C. The degradation becomes complete beyond 500°C. The silica feedstock shows a secondary peak around 420°C. The presence of alumina powder, used as the bed to de-binder silica components, however, enhances the kinetics of degradation strongly. The primary degradation occurs in a narrow range of temperatures around 200°C, along with a broader secondary peak around 280°C. The reason behind the narrow degradation range in the presence of alumina powder is not far to seek. Fig. 10 shows the injection molded low pressure turbine (LPT) blade green core thermally degraded at 210°C, along with a cross-section of the same. The surface of the core looks yellowish brown, but the interior portion, is white as seen in the cross section. The binder appeared to have drained off to alumina powder by capillary action, and degraded there. The large surface area that the alumina powder can provide for the degradation is responsible for such a narrow degradation peak. In addition to this, alumina catalyses the degradation also, by shifting the temperature of degradation downwards. The degradation also occurs with the evolution of a large volume of gaseous products. Taking into consideration these factors, one must plan to de-binder and sinter in stepwise manner to drain the binder into the support bed initially, and degrade it as slowly as possible so as not to disturb the weak particulate structure sprue. Once the degradation is complete, the temperature is rapidly raised to sinter the component.

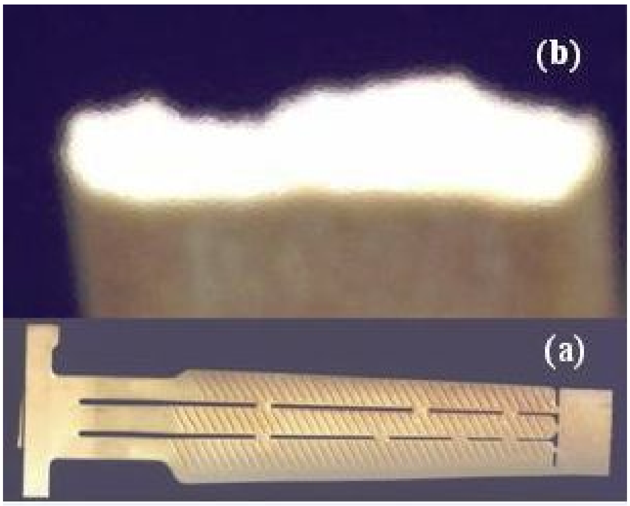



Fig.10 (a) LPT blade green core thermally degraded at 210°C. (b) Its cross-section

### 3.2.3 Sintering and finishing the core

The process of sintering of silica components is the same as that used for components formed by powder pressing techniques. The inter-particle bonding in this case occurs by viscous flow mechanism [(10),(11)]. The same mechanism also promotes de-vitrification of amorphous silica at these sintering temperatures [(12),(13)]. If the extent of de-vitrification is high, the components tend to crack while cooling below 300°C after sintering process as shown in fig. 11. This is due to the volume change associated with the high-low transformations associated with devitrified silica phases like cristobalite or tridymite. It is therefore essential that the sintering temperatures and times are to optimize appropriately to ensure that the component with the desired composition and properties are obtained. For ceramic cores, one has to also pay attention to the extent of de-vitrification that result during sintering, especially so, since the binder residues can catalytically affect the sintering and de-vitrification processes. [(14)]

Fig.11: Sintering crack on core

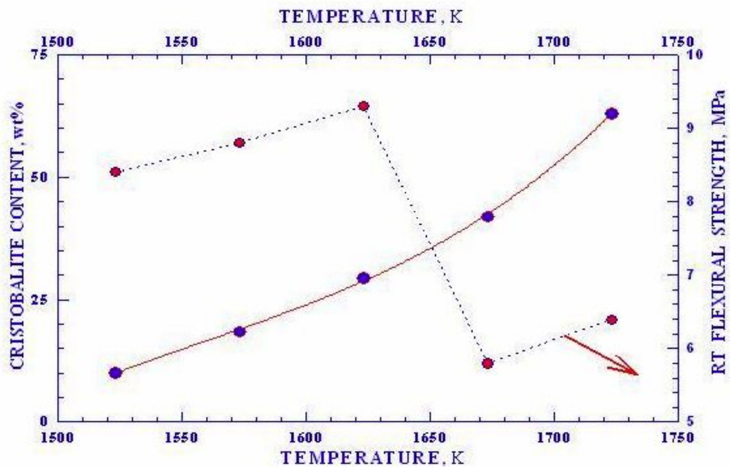



Fig.12: Variation of flexural strength with cristobalite content

Fig. 12 shows the 4-point flexural strength of silica samples along with the extent of cristobalite formed as a function of the sintering temperature. Once the cristobalite level in the sample increases beyond 25%, the strength drops drastically. Microstructure also indicates cracking of bigger particles corresponding to this, suggesting that the cristobalite levels should be kept to the minimum, to ensure integrity of the components during sintering. Ceramic cores with relatively simple shapes are produced employing slip casting or low-pressure injection molding technique. DS/SC airfoil parts of modern aero-engines with extremely thin and narrow serpentine channels however require high-pressure injection of slender and distortion resistant but collapsible, leach-able and inert ceramic cores to avoid dimensional deviation, hot tear, residual core and metal- core reaction. Optimum particle size, shape, distribution, chemistry and physical mixing of ceramic powders and appropriate binder and their ratio, injection temperature, pressure, rheology, scheme of binder removal, firing, impregnation and dressing of ceramic cores are the important factors to control strictly for production of acceptable cores.

### 3.3 Design and engineering of pattern assemblies

Above mentioned precision press molds along with intricate ceramic cores can now give rise to complex wax patterns with dimensional precision and aerodynamic surface finish by injection molding optimum wax formulations in controlled environment. Turbine airfoil castings employing such wax patterns are generally cast in assemblies of either individual airfoils or in segments of twin, triple or multiple airfoils depending upon the size, geometry and criticality of casting in hand and the casting process involved to enhance quality and production economy. Integral rotors and stator vanes are often assembled in precision assembly fixtures out of individually injected airfoil patterns. Simple integral rotors and stators with relatively wide gap between adjacent airfoils are injected in single shot into single die assembly having retractable airfoil inserts. All kind of assembled wax patterns however, are invariably clustered around appropriate sprue and pouring cup with optimum size, shape and location of in-gates, risers, feeders and vent holes necessary for de-waxing and vacuum casting. Wax clusters for DS/SC processing are designed around special clustering fixtures to produce bottom-open molds. Success in DS/SC casting of turbine airfoil casting depends greatly on the longitudinal as well as the azimuthal orientation of the individual parts clustered around the central sprue in order to maximize radiation view factor to the solidifying mass in the mold. Platinum pinning and slide joints at strategic locations on the cores are the order of the day for thin walled castings.

### 3.4 Casting technique and engineering

Vacuum induction melting and investment casting has produced turbine airfoil castings since nineteen fifties and for almost all the modern aero engine gas turbines even now. A number of variants of this technology such as Bridgmann technique and liquid metal cooling (LMC) have evolved to bring out superior products. Conventional equiaxed casting also has been suitably modified to produce fine grain structure (ASTM no. 2) throughout the section of integral rotors irrespective of having thin airfoils and thick hubs for better fatigue resistance. This has been possible by melt churning or pulsating, the melt during freezing to break the growing dendrites into fragments which could serve as fresh nucleation sites. DMRL has developed this casting technology for a variety of integral rotor wheels and stator rings (figure-13) for the jet fuel starter (JFS). More than 40 engine sets of type certified JFS castings have been delivered, which are currently being used in developmental flights. DMRL could develop directional solidification technology in the year 1990 for turbine blades and vanes shown in figure-14 of an indigenous aero-engine incorporating state of the art cooling schemes from impingement to serpentine and film cooling combined with extremely thin wall and very tight metallurgical and dimensional limits. This was possible by employing open bottom shell molds clamped on to a water cooled chill block which could hold molten metal above 1500°C and allow it to freeze from bottom of the mold towards top as the mold was slowly withdrawn out of the mold heater across a steep temperature gradient maintained at the nearly flat and stationary solid-liquid interface. Successful castings could be produced using suitably developed shell molds and cores, which could resist creep, distortion and metal mold reaction against hydrostatic pressure of the molten metal.

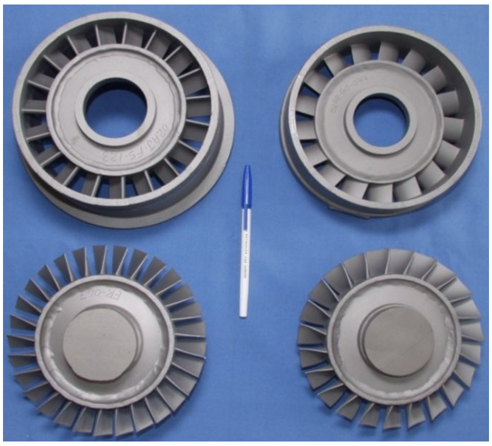
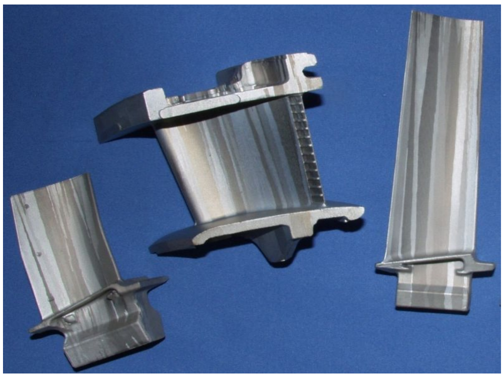


Fig. 13 (a) Integral stator and rotor; (b) Coarse grain conventional casting (above) Melt churned fine grain casting (below)



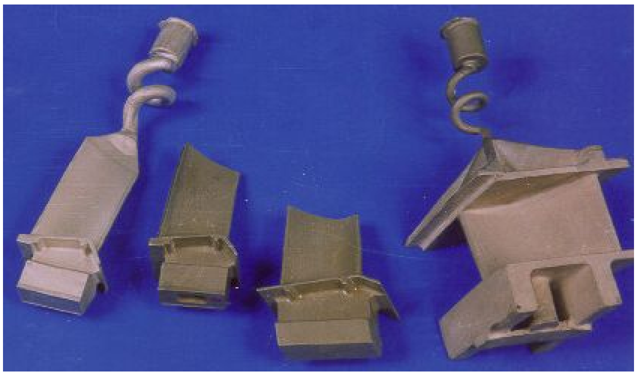


Fig. 14: (a) Hollow DS blades in alloy DMD4. (b) Single Crystal blades in alloy DMS4.

SC turbine blades could be produced as shown in figure-14 (b) by providing a constriction between the starter and the blade of the DS mold to allow only one grain to grow into the entire mold cavity. Directional heat flow from liquid metal to the solidified metal by conduction could be maintained across the solid-liquid interface of less than 6mm diameter helix cross-section due to the steep temperature gradient and then from the solidified metal via the mold to the water cooled wall of the furnace by radiation in the Bridgmann process. DMRL has recently developed a novel technique to make integral rotor castings with columnar-grained blades for better creep resistance together with fine-grained disc in a single casting step for better fatigue resistance as shown in figure-15. This was possible by advancing initially a circular solidification front from the blade tips across a steep temperature gradient discouraging nucleation up to rim then switching over instantly to the condition of rapid nucleation from rim into the entire disc.

Fig.15 Integral rotor wheel with hybrid grain structure made in a single casting step

**4. Future Direction**

Development of gas turbine airfoil materials all over the world is being focused to push temperature-capability of blade material well above 1100°C with reasonable environmental resistance. Significant improvement has been made in TET with enhanced metal temperature capability of cast Ni-base superalloys by increasing total refractory element content beyond 20wt%. Any more increase in refractory elements of these alloys will be prone to phase instability. Further rise in metal temperature capability can however be realized by incorporating platinum group of metals which will not only push the alloy liquidus and mechanical properties up and ensure phase stability due to their higher solubility according to their binary phase diagrams with Ni and due to Ni-like FCC structure, but also enhance hot corrosion resistance being the noble metals. It will be wise to either replace or partially substitute the current alloying elements such as Mo and W with platinum group of metals since, Mo and W are known to form topologically closed packed (TCP) oxidation prone phases. Alloying additions of platinum group of metals in turbine airfoil materials in view of their high cost may be pursued for high performance military aero-engines, where mission objectives are the over-riding factors instead of cost. LMC offers more efficient heat transfer from the solidified metal via mold into a pool of low melting liquid metal by conduction unlike radiation in Bridgmann process. (15) It allows 2 to 3 times faster mold withdrawal rate relative to Bridgmann process leading to finer dendrites, reduced segregation and higher component yield of advanced generation superalloy single crystal blades being with heavily loaded refractory elements. It will be advantageous not only for tall blades with large cross section and wide chord but also for less than 0.5mm thin walled aero-engine blades to have more than one load bearing primary dendrites apart from effective homogenization, optimum and well aligned $\gamma'$ structure, volume fraction, size, shape and misfit in $\gamma$-matrix. TET can be further improved either by refractory metal (Ir, Pt based) superalloys or by engineering transpiration cooling scheme instead of convective and film cooled blades. Cost effective production of hybrid rotors and stators with creep resistant DS blades and fatigue resistant fine-grained hub for reusable small aircrafts in military and nonmilitary applications is another area of interest. Epitaxial growth of functionally graded aerofoil castings with desired texture in micro-layers of refractory noble metals with intricate cooling channels, followed by oxidation resistant inter-metallic and thermal barrier ceramic layers may become the next choice since current ceramic molds or core systems cannot survive above 2000°C to shape these materials into turbine airfoils and the cost of these materials will also prohibit any waste as sprue, riser, in-gates through bulk melting and casting.

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