Chapter 15
Defence Metallurgical Research Laboratory: Relentless Journey Towards Materials Galore

G. Madhusudhan Reddy

15.1 Introduction

Defence Metallurgical Research Laboratory (DMRL) at Hyderabad had its origins as one of the earliest laboratories under the umbrella of the Defence Research & Development Organization (DRDO) during 1958. DMRL was initially carved out of the Technical Development Establishment (Metals), which was earlier called the Inspectorate of Metals and Steel, situated at Ichhapore (near Kolkata). Upon subsequent shifting to Hyderabad during 1963, DMRL made rapid strides in the development

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of several strategic materials of particular interest to defence with applications in aircraft, ships, tanks, electronics, and missiles.

DMRL, tasked with the primary objective of design and development of advanced metallic, ceramic and composite materials, had also contributed significantly to the related processing technologies to meet the needs of the system laboratories of DRDO and armed forces as well. DMRL developed numerous strategic materials/ technologies with specific applications of interest to defence forces during its nearly six decades of service to the nation—DMRL's R&D found direct applications in aircraft, ships, tanks, electronics, and missiles too. Simultaneously, DMRL's scope of functioning continued to grow encompassing friction materials, heavy alloys for armaments, steel projectiles and armour, ultra-high strength low-alloy steel, titanium and titanium-based alloys, nickel-based super alloys, investment casting of super alloys for aircraft applications, magnetic materials, etc. Over the years, the laboratory has acquired a special status as a premier centre for R&D in metals, alloys, ceramics and composites. Currently, the multidisciplinary core competence at DMRL includes diverse areas such as product engineering, production support and performance analyses on metallic/alloy/composite parts, process development & surface engineering, extractive metallurgy of Ti/Mg/Rare-earth metals, design & development of speciality alloys/intermetallics/ceramics/composites. The laboratory's efforts have resulted in significant contributions to DRDO systems, the armed forces, and civilian spin-offs as well. DMRL has also made a very prominent long-standing niche for itself in Failure Analysis support to the armed forces, apart from several civilian spin-offs such as the development of turbine blades for civilian energy applications, Cu-Ti anti spark tools, and many bio-medical devices.

The R&D contributions at DMRL have led to the formation of new technology and production centres in the country. They are: Mishra Dhatu Nigam (Midhani), Hyderabad, Heavy Alloy Penetration Plant (HAPP) an Ordinance Factory, Tiruchirapalli, Non-ferrous Technology Centre (NFTDC), Hyderabad, and International Advanced Research Centre for Powder Metallurgy Materials (ARCI), Hyderabad. Today, each of them is a nationally important organization in its own right.

15.2 Core Competence

Over the years, DMRL has established core competence in the following areas of metallurgical engineering and materials science:

- Knowledgebase in process-structure–property-performance relationships of advanced materials
- Design and development of speciality alloys, intermetallics, ceramics and composites, process development and surface engineering
- Extractive metallurgy of titanium, tungsten and magnesium
- Product engineering, production support and performance analyses of metals, alloys and composites

The laboratory's efforts are directed towards the development of capabilities and technologies that are crucial for high-end defence systems, but not readily available from foreign sources due to strategic or other reasons. Over the years, DMRL has developed and matured several technologies catering to the requirements of systems for various defence applications in crucial areas such as armour, ammunition, missile, aircraft, and naval systems.

The significant scientific and technological achievements of the laboratory in recent years are briefly summarized in the following pages.

15.3 Protective Armour Technologies

Over the past four decades, under a number of technologies driven projects, DMRL has indigenously developed and provided protective armour technologies for a wide range of combat platforms for all of our tri-service armed forces. The most notable among them include composite armour for main battle tanks (MBT), infantry combat vehicles (ICV), helicopters, body armour, upgrades for ICVs, and Wheeled Armour Platform (WhAP).

Protective armoured vehicles: (a) MBT, (b) Helicopter, and (c) WhAP

Several advanced metallic, ceramic and polymeric materials have been developed by DMRL, in close collaboration with various industries and academic institutions. Each of these materials technology applications has emerged as an outcome from years of extensive efforts on process development, scientific understanding of process-structure–property relations, and critical analyses of the ballistic & impact immunity against various threats.

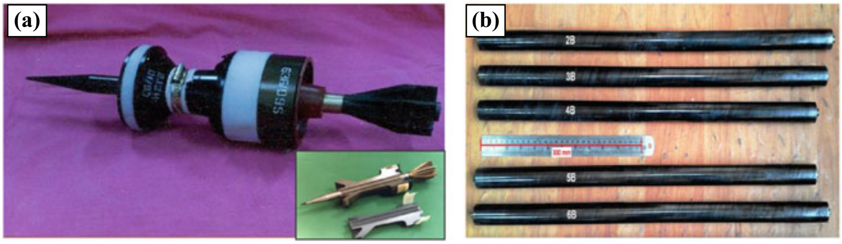
With a constant increase in the demand for increased ballistic protection with a relatively lower weight penalty, DMRL has constantly been pursuing the development of advanced protective armour technologies for next generation weapons platforms. Futuristic developmental efforts have been in place all along through progress in realization of advanced lightweight materials, supported by modelling & simulation, optimally scaled ballistic & blast tests, and advanced imaging & diagnostic techniques-thereby contributing to India's complete self-reliance in this highly specialized domain.

15.4 Ammunition Technologies

Catering to the requirement of ammunition materials for the Indian defence, the army, in particular, is one of the major thrust areas of research at DMRL. The earliest success story in this domain was in the development of tungsten heavy alloy cores (also known as long rods) in Fin Stabilized Armour Piercing Discarding Sabot (FSAPDS) for MBT during the 1980s. A production agency for FSAPDS named Heavy Alloy Penetrator Project (HAPP) was established at Tiruchirapalli and successfully mentored by DMRL, as part of a joint initiative between DRDO and OFB. Significant quantities of KE penetrators, meeting the specified Depth of Penetration (DOP), have been supplied to army subsequent to the inception of HAPP.

The continual emergence of improved levels of armour protection in the Armoured Fighting Vehicles (AFV) has given rise to demands for enhanced ballistic performance in penetrators in the form of relatively higher DOPs. The cores to meet the requirement of higher DOP penetrators were developed at DMRL, using a W–Ni-Fe-Co alloy subjected to double swaging with an appropriate inter-pass heat treatment, realizing improved properties at desired lengths thereby resulting in successful firing trials.

DRDO has also initiated the development of an enhanced penetrator, in terms of consistent performance and higher DOP. The improved design relies heavily on cores of higher density and thus higher tungsten content. This has largely been achieved by optimizing the processing parameters. The development of cores being successful, a decision has been taken to validate their effectiveness through firing trials.



KE penetrators: Full Assembly: (a) FSAPDS and (b) WHA penetrator (long rod)

15.5 Shaped Charge Warhead Liner Technology

Shaped charge warhead liners are used in the weaponization of small & medium calibre armaments. DMRL has established the expertise in resolving metallurgical concerns through scientific determination of material chemistry, development of thermo-mechanical schedule to achieve the desired structure and properties, and development of suitable fabrication methods to realize the liner geometries. The tantalum explosively formed penetrator (EFP) liners developed by DMRL were successfully deployed in the technology demonstration of multi-layer penetration by the static missile systems developed by DRDO. Further, the EFP liners developed from the high purity Iron plates developed by DMRL were assessed for applications in Sensor Fused Munitions (SFM).

Shaped charge liners

Presently DMRL is working on the processing technologies for liner materials to facilitate the development of state-of-the-art warhead technologies, such as the Follow Through Warhead (FTW) technology and Low L/D shape charge warheads technology. Additionally, the processing route for certain advanced liner materials has also been successfully established.

15.6 Technologies for Naval Steels

DMRL has successfully developed technologies for the indigenous production of low-alloy speciality steels in the form of plates and bulb bars for naval applications, with the R&D efforts initiated during the year 2000. The initial lab-scale development was carried out in collaboration with NMRL, while the scale-up to industrial production was realized through SAIL and a few private firms as well. The Indian Navy strongly supported DMRL, both during the development and production efforts, finally culminating in the acceptance of the steels for naval use after due qualification. The steels are currently being used for the navy has also designated DMRL developed low-alloy steels as the standard default material for all new constructions and repairs of warships in future.

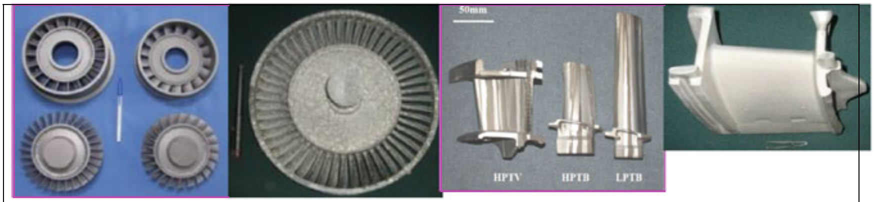
A large quantity of these steels, to the tune of thousands of tonnes, has already been supplied so far for fabrication at the industries. The indigenous plates and bulb bars are considerably cheaper than their imported equivalents. This has benefited the nation through substantial savings in fabrication cost and foreign exchange requirements.

INS Vikrant – the first Indigenously Aircraft Carrier developed by India at Cochin Shipyard

Type certification of the steel plates and bulb bars, which is mandatory for its underwater applications and simultaneously, efforts at establishing the indigenous production of high strength steels and their certification for underwater applications has been concluded, sucessfully achieving all major objecvtives., i.e., estabilshed indigenious production of high strenth steel semi-products under Russian consultancy using indigenous facilities.

15.7 Investment Casting Technologies for Superalloys

DMRL has been involved for the past several decades in the development of various technologies towards the production of Ni-base superalloy components, for advanced gas turbine engines, through vacuum investment casting route. These hot section components such as turbine blades, vanes, and rotor blisks are extremely complex in their geometry and characterized by close dimensional tolerances. During the initial stages (up to 1990s), equiaxed solid aerofoil components such as low and high pressure turbine blades were developed and supplied for aeroengine development efforts of DRDO. Equiaxed casting technology was also used recently for the development and supply of several critical components for a small turbo-fan engine (STFE) developed at GTRE. As the requirement for components with higher temperature capabilities increased, the technologies for the production of hollow components with complex internal air cooling channels were developed. Simultaneously, during the 1990s, the task of development of ceramic cores for investment casting of hollow aerofoil components was undertaken by a dedicated team at DMRL.



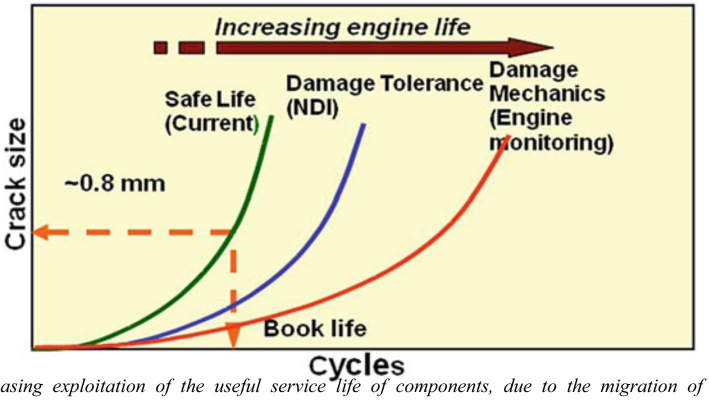
(a) **(b)** **(c)** **(d)**

Some of the gas turbine engine components developed at DMRL: (a) equiaxed components for jet fuel starter for Tejas aircraft, (b) low pressure turbine rotor blisk for small turbo-fan engine (STFE) used for powering unmanned air vehicles (UAVs), (c) DS blades and vanes for Kaveri engine and (d) SX vane casting currently under development for use in advanced aircraft engines.

During the development of Kaveri gas turbine engine (1990–2000), another technological milestone was surpassed in the form of development of a large number of directionally solidified hollow aerofoil components (such as the low & high pressure blades and vanes) for GTRE. Subsequently, the directional solidification (DS) casting technology was transferred to HAL, Koraput for industry-scale production of components. During 2015, the strategically important and unique single crystal (SX) component technology was also developed at DMRL. The demonstration of industrial viability of this technology is presently underway for the production of SX blades and vanes in large numbers for meeting GTRE's requirements. Additionally, DMRL is also working on futuristic technologies such as the production of double-wall SX aerofoil components, which are expected to possess significantly higher temperature capabilities in comparison to their single-wall counterparts. Further, environment friendly technologies such as recycling of pattern waxes and superalloy scrap for the production of aeroengine components are also being pursued at DMRL.

15.8 Life Prediction Technologies for Aero-Engine Components

Gas turbine aero engines accumulate damage in service as a result of their demanding operating conditions. This damage can manifest in several forms depending upon the component, engine type, and its operating environment. Replacement of service-damaged parts is expensive and is a significant factor to reckon in the life cycle cost of engines. Structural Integrity may broadly be quantified in terms of permissible usage in the service environment before crack nucleation (Safe-Life), crack propagation (Damage Tolerance (DT)), and evolving damage (Continuum Damage Mechanics (CDM)). The gains due to migration from safe-life to DT to CDM in the context of an aero engine lifting, with particular reference to fatigue loading and consequent failures, are quite significant.



Increasing exploitation of the useful service life of components, due to the migration of design philosophy from Safe-life to DT to CDM.

DMRL has taken up evaluation of the potential for revision of Time Between Overhauls (TBO) of a unique Thrust Vector Control (TVC) jet nozzle of an advanced fighter aircraft engine and the Total Technical Life (TTL) of a transport aircraft engine—both systems being essential for IAF from an operational point of view. Both the tasks were successfully executed and the TBO life of TVC jet nozzle was doubled from OEM recommended limit and implemented in IAF fleet, after certification by CEMILAC. The upward TTL revision by about 15% for the transport aircraft engine was scientifically established and CEMILAC's approval is awaited for implementation in IAF. Simultaneously, the Science & Technology aspects of Remaining Life Assessment (RLA) of high temperature gas turbine components were also established.

A project on revision of TTL of an advanced gas turbine engine has been taken up by DMRL and is currently in progress. The project is aimed at developing a scientific understanding of assessing the remaining life of in-service jet engines powering advanced fighter aircraft. The methodology to be followed for RLA involves application of a variety of modelling techniques in combination, to ultimately quantify the level of degradation in materials of critical components as a function of service usage. This is a highly multidisciplinary and multiagency project, with DMRL functioning as the nodal lab for execution under aggressive PDC timelines-to cater to the immediate operational requirements of IAF.

15.9 Extraction of Reactive and Refractory Metals

15.9.1 Titanium Sponge

Titanium sponge is the nascent form of titanium metal, obtained through the high temperature reduction of $TiCl_4$ (Kroll process). DMRL has developed state-of-the-art Kroll technology in 3500 kg batches through extensive experimentation, equipment engineering, scientific understanding of the process technologies, advanced process instrumentation, and exhaustive data logging. The technology was demonstrated at DMRL on a lab scale and subsequently transferred to KMML, Kerala for establishing the titanium sponge plant for indigenous production. The plant has a capacity of 500 MT/year and was supported through funding by VSSC. The plant is now in regular operation and meeting the requirements of aerospace and defence programmes of the country. DMRL has also completed type certification of the titanium sponge produced at KMML for critical aero and naval applications, in close association with KMML and VSSC. DMRL has also filed an Indian patent on this process development.

High purity titanium sponge cake (3500 kg)

500 tpy titanium sponge plant at KMML established with DMRL technology

15.9.2 Magnesium

Fused salt electrolysis of anhydrous magnesium chloride ($MgCl_2$) a by-product generated during the production of titanium sponge, is developed to produce magnesium metal and chlorine gas, as an integral part of the commercially economical production of titanium sponge. The process essentially consists of the electrolysis of $MgCl_2$ in a pressure tight electrolytic cell operated at 690–700 °C. DMRL carried out extensive pilot plant operations of mono and multi-polar magnesium cells with a view to develop the technology for the production of magnesium metal at the rate of about 300 kg/day. Different types of cells were designed, developed and operated. The salient features of the process technology include molten salt feeding system, two module 5-bipole electrolyte zones, and a fool proof chlorine collection & neutralization system. Several hundreds of tonnes of $MgCl_2$ in each cell operation helped in the generation of valuable process engineering data. DMRL signed MoUs with NFC, DAE and VSSC (ISRO) for establishment and operation of Mg pilot projects with the technical knowhow developed at DMRL.

15.9.3 Tungsten

Tungsten metal is of significant strategic interest to defence and India has been importing the metal for the manufacture of various types of ammunition systems for the armed forces, such as FSAPDS at HAPP. Since China currently dominates global supplies of tungsten metal powder, it is felt essential to develop the indigenous tungsten supply chains.

DMRL in collaboration with two CSIR laboratories developed the processing technologies for the production of tungsten metal from heavy alloy scrap, Ammonium Paratugnstate (APT), and tailings material (process waste) accumulated at Hutti Gold Mines, Karnataka. Based on the pilot plant data of the extraction/recycling process technologies, it is proposed to establish and operate a technology demonstration plant of 100 MT/year capacities in association with an interested production agency.

15.10 Titanium Alloys for Aircraft Components

Over the past few decades, DMRL has been the nodal agency for the indigenous development of titanium alloys for defence applications. The primary alloy melting, processing, and characterization was routinely carried out at DMRL followed by industrial scale melting and processing at MIDHANI. DMRL has successfully undertaken alloy development and the realization of relevant components for the following alloys. (i) Ti-10V-2Fe-3Al is a high strength metastable beta Titanium alloy for closed-die forged components. Under the ADA funded project, melting and thermomechanical processing of cylindrical bars, to diameters of 60 and 100 mm, was completed together with type certification for their future programmes. The alloy will replace many steel components, resulting in considerable weight saving (ii) Titan 44 is a beta Titanium alloy used for applications in sheet form. It possesses excellent oxidation resistance because of higher Mo content. Despite being a beta Titanium alloy, its creep properties are comparable to those of Ti-6Al-4V. The technology for melting was established overcoming the challenge of non-availability of proper Al-Mo master alloy. A pilot melt has been processed to 2, 1.2 and 0.8 mm thick sheets to sizes 1100 × 1000 mm together with extensive property evaluation for aerospace applications. Two more melts and complete type certification are proposed to be undertaken in a new project.

Currently, DMRL is pursuing the Titanium alloy development and component manufacturing technology for AMCA structural application that involves: (a) Development of Ti-5Al-5Mo-5V-3Cr high strength deep hardenable beta Titanium alloy slabs of 200 mm thickness and higher for aircraft forging applications, (b) Development of Ti-6Al-4V slabs of 1300 × 1200 × 120 mm size, (c) Large size closed-die forgings of Ti-6Al-4V, (d) Development of investment cast components of Ti-6Al-4V, and (e) Manufacture of large size bulkhead frame from Ti-6Al-4V plates and forged sections by machining and welding. Presently DMRL is also providing expert consultancy for indigenous development of alpha Titanium alloys viz. BT1-0, PT-3B and PT 7M in various product forms for naval applications.

15.11 Powder Processing Technologies

DMRL has established unique Hot Isostatic Press (HIP) and Cold Isostatic Press (CIP) facilities during the mid-70s, for the manufacture of critical rotating components of defence systems. A broad-based expertise on several aspects of the isostatic pressing technology for different high temperature materials has been developed. DMRL has launched a hardware oriented indigenous R&D effort to establish a unique P/M (HIP) processing technology for the manufacture of Integral Turbine Rotors. The HIPed integral rotors were successfully produced out of stainless steel for one of the missiles and Ni-base superalloy rotors (both in monolithic/dual-materials) for space applications (GSLV, ISRO). DMRL has also established an advanced HIP technology for defect healing of investment cast components from Aluminium alloys, Ni-base superalloys and Titanium alloys for applications in military aircraft, missiles, and submarines respectively.

The HIP technology of DMRL was also adapted to the diffusion bonding of high strength special steels and fabrication of Test Blanket Modules (TBMs) for applications in fusion reactors. DMRL has recently established a sophisticated Inert Gas Atomisation (IGA) facility. Production of high-quality powders from different grades of superalloys for aeronautical applications (through HIP & 3D Metal Printing) has been demonstrated successfully. Simultaneously, indigenous development of P/M superalloys was also pursued through modelling and simulation resulting in the identification of a set of 5 new optimized alloy compositions. The development, production, and processing of these new alloy powders will be carried out by adopting the *Integrated Computational Materials Engineering* (ICME) approach to significantly save on the developmental time, funds, and efforts.

As part of one of the current projects, DMRL has taken up an exciting R&D effort towards the development of P/M Ni-base superalloy aeroengine discs with improved performance to meet the futuristic needs of military aircraft and helicopters. The sub-size superalloy N18 discs with targeted properties have been realized through innovative HIPing and near isothermal forging, duly followed by a novel heat treatment procedure. The technology established under this project will benefit immensely the aeroengine programmes of DRDO.

In the recent past, DMRL has developed a unique technology based on CIP and Sintering for the manufacture of fused silica radomes for high-speed target seeking missiles. This CIP technology has been transferred to major industries for industry-scale production. Further, DMRL has taken up an independent project for the development of ceramic radomes with high strength and high temperature capability for application in hypersonic missiles.

15.12 Materials for Hypersonic Vehicles

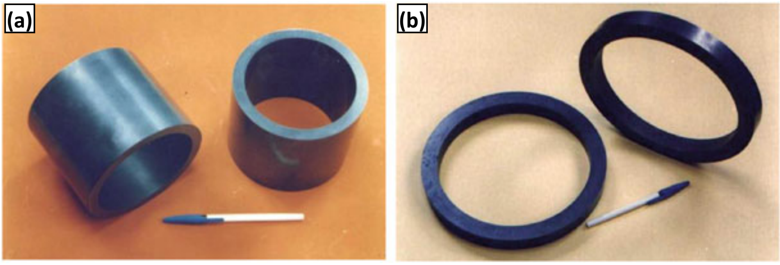
The objective of the project *HYPERMAT* was to develop materials and coatings for long duration hypersonic vehicles, apart from establishing specialized test facilities for their characterization. Owing to the severe aerodynamic heating during flight, the surface temperatures are expected to reach up to 1300 °C at the critical locations on control surfaces such as leading edges, nose tips, etc. Technology has been developed at DMRL to produce C_f-SiC panels as well as nose tip and leading edge shaped composites. A totally indigenous laboratory-scale CVI-CVD facility has also been established. Technology has been developed to synthesize the ZrB_2 powder on a 5 kg batch scale and to vacuum hot press it into 150 mm diameter discs, when temperatures encountered are expected to significantly exceed 1300 °C. Box type, truss type, and foam based metallic thermal protection system (MTPS) of cross-section 300 × 300 mm have been developed to protect the airframe. Technology has been developed using electron beam melting/vacuum arc melting to produce niobium based Cb 752 alloy sheets of 300 × 300 × 4 mm size possessing target composition and properties for the scramjet combustor. Protective coatings have been developed at coupon-level for all the materials developed in the project. All the important characterization facilities such as Gleeble, Laser Flash, IR Heating, and the Induction Plasma Erosion and Coating (IPEC) facility as envisaged in the project have been established and used extensively for the characterization of the above material. Since all the objectives of this project have been successfully realized, DMRL is currently working on developing an in depth understanding on manufacture and scale-up related issues in respect of the above materials. This is expected to be a significant step in the realization of the crucial hardware for the development of futuristic hypersonic vehicles.

15.13 Liquid Silicon Infiltration (LSI) Technologies

15.13.1 Reaction Bonded Silicon Carbide (RBSC)

Silicon Carbide is the most widely used structural ceramic material, for both ambient and high temperature applications. Among the two processing routes for consolidation of Silicon carbide, processing of Sintered Silicon Carbide (SSC) involves sintering temperature >2100 °C and >20% resultant volume shrinkage. On the other hand, processing of Reaction Bonding of Silicon Carbide (RBSC) is carried out at 1500–1600 °C by Liquid Siliconisation Infiltration (LSI) and the resultant volume shrinkage is marginal (~1–2%). DMRL has taken up the development of Reaction Bonded Silicon Carbide (RBSC) bearing bushes and thrust bearings to circumvent the restrictions imposed on the import of these critical components for the indigenous nuclear submarine program.

DMRL has established the processing facilities and optimized the plan for realization of RBSC with excellent high temperature strength in excess of 1000 °C, very high hardness (2500 VHN), and wear resistance. In the Reaction Bonding process, molten silicon infiltrated into the porous SiC/C preform, chemically reacting with the carbon to form secondary grains of SiC to bond the primary grains of SiC resulting in a near-net shaped dense RBSC product. However, the presence of some amount of free silicon limits its application temperature to below the melting point of Silicon (1410 °C). The RBSC Bearing bushes and Thrust Bearings developed by DMRL have been fully qualified by DMDE before their induction in the main feed water pumps for submarines. The RBSC technology was transferred to International Advanced Research Centre (ARCI) and industry through a MOU to fulfil the requirements of Navy on royalty sharing basis.



Reaction Bonded Silicon Carbide (RBSC) bearing parts: (a) RBSC Bearing Bushes and (b) RBSC Thrust Bearings

15.13.2 C_f-C-SiC Jet Vanes

Jet Vanes are the part of Thrust Vector Control (TVC) mechanism in interceptor missiles, where direction of flow of exhaust gases is controlled by a set of jet vanes to steer the missile in the required direction. The jet vane material should withstand highly erosive combustion gases with marginal levels of erosion at extreme temperatures and high speeds. DMRL, together with DRDL and ASL, developed a new composite material C_f-C-SiC. The expertise and facilities of DMRL in the area of Liquid Silicon Infiltration (LSI) were employed in the rapid development and validation of C_f-C-SiC composites for jet vane applications. These low density vanes could successfully withstand the high rate of erosion (due to the presence of SiC), high thermal shock (due to the presence of highly conductive carbon fibres), and also retain their high temperature strength.

The C_f-C-SiC vanes have been static tested for their performance at high temperatures using char motors and six component test beds. A protective collar was incorporated in jet vanes to overcome the jamming of the jet vane at its bearing due to the molten alumina present in the exhaust, enabling DRDO to successfully accomplish the first flight trial of interceptor missile. The effective team work by DMRL-DRDL-ASL resulted in achieving self-reliance in the area of C_f-C-SiC jet vane technology.

This material has become the lifeline for several other missile systems too. To take this development forward, ASL established the production facilities to exploit the LSI processed C_f-C-SiC composites to cater to the requirements of missile complex, thereby saving a significant amount of foreign exchange.

15.14 Near Net Shape Technologies

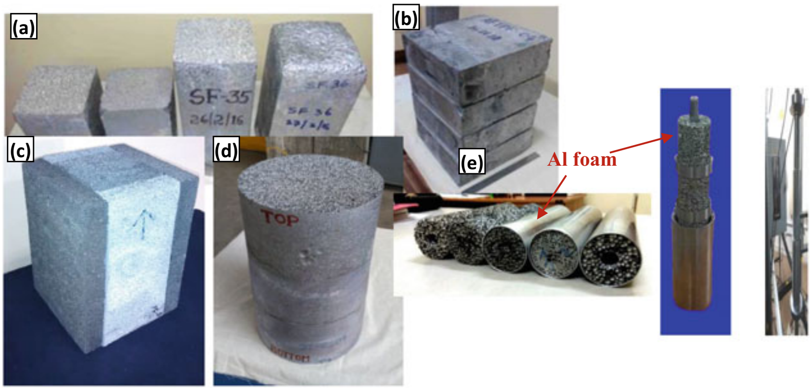
Using a unique 2000 MT hydraulic forge press, DMRL established the indigenous near isothermal forging technology to produce critical class-I components through a scientific methodology involving Dynamic Materials Modelling (DMM) and Finite Element Analysis (FEA). The rotor disc of 1–5 stages of the high-pressure compressor (HPC) was realized, out of a difficult-to-deform titanium alloy similar to IMI-685 for a military gas turbine aeroengine. The indigenous technology has been transferred to MIDHANI and the bulk production of these disc forgings is successfully being carried out by the firm using DMRL's forge press on cost basis. On similar lines, (a) HPC discs and compressor front shaft out of titanium alloy equivalent to IMI 834 for Kaveri Engine and (b) HPC components for aeroengine have also been forged, qualified, and supplied to GTRE. Indigenous technology to manufacture a mountaineering accessory Karabiner, out of an aluminium alloy has also been established and the technology was transferred to the Ordnance Factory Dehradun. Till date, 59,228 nos. of the Karabiner have been manufactured by the industry and supplied to the Indian Army.

15.15 Electronic Materials

DMRL has been working on electronic materials over the past two decades, a first of its kind effort in the country, with a unique core competence in the nano-level characterization of electronic and opto-electronic materials. Several projects were successfully completed in collaboration with SSPL/GAETEC on high-frequency devices, photonic device structures, and functional materials. Strategic significance of the single crystal SiC applications encouraged the initiation of a research activity during 2009, partnering DMRL and SSPL, leading subsequently to a joint S&T project in 2015—with the objective of developing SiC single crystal bulk growth and wafer fabrication processes. DMRL thereby successfully established the single crystal SiC technology, in association with SSPL and C-MET. Several issues with the technology were effectively addressed including the SiC single crystal growth, SiC wafer fabrication, SiC material's physical/electrical properties' characterization, process modelling, and deposition of the GaN epitaxy on indigenous SiC wafers. Presently, efforts are in place to develop the SiC devices for defence applications—especially sensors for harsh environments and high-power devices. A multidisciplinary effort is also being launched in association with numerous R&D labs/academia/foundries with relevant expertise in the domain.

15.16 Metal Foam Technologies

DMRL had successfully established the technology to produce closed-cell aluminium foams through the melt route, by way of mixing fine TiH_2 (Titanium Hydride) particles into the aluminium melt. Numerous fine cells are generated in the melt due to the release of hydrogen from the particles, which subsequently grow and form cells of 2–4 mm size. Aluminium foam ingots of 175 × 175 mm cross-sections of 400–700 mm lengths, plates of 300 × 300 × 100 mm sizes, and with a density of 0.3–0.7 gm/cc were successfully produced through this technology. Due to the unique hexagonal structure of the cells, foams could absorb high impact and blast energy at a low transmitted stress. Product shape, size, cell uniformity, and consistency in the foam quality are important factors from the application stand point. These specifications were successfully achieved through several process optimisation experiments and innovations. Modelling and simulation were also carried out simultaneously to explain the mechanisms of cell structure evolution, apart from understanding the deformation mechanics of cells in impact and blast situations to enable the eventual optimisation of component designs.

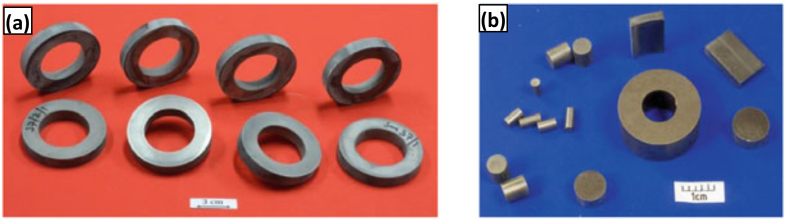


Al-foams produced through melt route: (a) Ingots, (b) Plates; Impact absorbers given to BARC (c) 285 x 285 x 400 mm size, (d) 300 dia. X 400 mm length size and (e) Energy absorbers designed by DMRL / DRDL

Various foam-based impact absorber components were fabricated and supplied to several DRDO laboratories and external agencies viz., OFB, BARC, TBRL, HEMRL, and DRDL for various applications' trials. DMRL also provided an aluminium foam impact absorber component to BARC, which could successfully absorb 90 kJ of energy at an average transmitted force of <100 gm force (as specified by the user). Similarly, for an application related to missile launches, an aluminium foam-based impact absorber with high L/D ratio was successfully designed and evaluated at high strain-rates, which displayed the desired energy absorption characteristics. The successful development of this technology and the increasing demands for it resulted in the initiation of ToT to industries, which is currently in progress. Two industries have come forward with interest in the technology and technical assessment of the industries is currently in place.

15.17 Advanced Magnetic Materials Technology

Over the past five decades, DMRL has developed technologies for the production of state-of-the-art permanent magnets, catering to the strategic needs of the country through AlNiCo magnets in the sixties and seventies. These achievements were followed by subsequent efforts on the development of more powerful Rare Earth based SmCo and NdFeB magnets. The contributions of DMRL were instrumental in meeting the requirements of defence R&D programmes in several navigational devices such as gyros, accelerometers & TWTs, and motor transmissions for torpedo launchers etc. The efforts at DMRL also resulted in the Transfer of Technology to M/s IREL (India) Ltd to establish first of its kind REPM production facility at Vishakhapatnam using indigenous resources.



Typical permanent magnet components developed for applications in strategic technologies of defence, space and atomic energy sectors: (a) ring magnets and (b) various shapes of magnets

During recent years, DMRL has widened its focus on thin film magnetic materials for miniaturized sensor and actuator applications and a dedicated Class-1000 clean room facility has been established. DMRL has successfully developed different functional thin films and prototype devices based on spintronics, magnetostrictive, multiferroics, hard magnetic thin films etc. with desired functional properties for strategic applications. Typical devices have been successfully demonstrated for application in monitoring air pressure and controlling of wing movements in micro-aerial vehicle (MAV) which can be used for security surveillance and magnetic field sensors for naval applications. Stray magnetic fields of naval systems such as submarines and war ships need to be minimized in order to avoid detection by sea mines. These sensors will be useful in the detection and de-gaussing of stray magnetic fields of naval systems.

15.18 Advanced Metal Joining Technologies

DMRL has made significant contributions to resolving a wide range of fabrication issues by establishing welding technologies for similar & dissimilar welds of several advanced materials such as ultra-high strength steels, aluminium & titanium alloys, metal-matrix composites, ceramics and superalloys. Focussed research at the lab has promoted the engineering applications of these advanced materials in a big way through innovative fabrication techniques for realization of various defence systems such as combat vehicles, missile casings, base-mortar structures, nose-cap shell for an underwater launched missile, and compact heat exchangers. DMRL has also brought out the key influence of electron beam oscillation and pulsed laser beam techniques in reducing the Laves phase during the welding of superalloys, thereby improving the mechanical properties of aeroengine components. Further, a significant breakthrough was achieved by establishing ballistic capabilities in the welds, comparable to those of parent armour. DMRL's sustained initiatives, leadership, and dedicated efforts have resulted in the establishment of exclusive Friction-Stir Welding (FSW) &Processing Technologies, thus elevating DMRL to a unique position in the country in the manufacture of aerospace components at the national level. DMRL successfully fabricated the Nose-Cap shell for an underwater launched missile, through an innovative application of FSW for the first time in the country at the shop-floor level.

15.19 Tribological Technologies

DMRL has developed rigorous scientific understanding on the Tribological behaviour of advanced materials and associated coatings, in an effort to evolve state-of-the-art surfacing technologies for major systems for DRDO. Various types of coatings such as abradable, wear resistant, thermal barrier and dimensional restoration surfacing were developed.

A successful application of DMRL's research in tribology was towards the development of a solid lubricant for use in the canister of a long-range missile. The coefficient of friction between the Aluminium support blocks and canister of the missile had to be at a low value to meet the design requirements, that too at very high contact interface stresses. A suitable solid lubricant coating system has been developed on the Aluminium support blocks to reduce friction by 75%. The coated support blocks are now being used in all canisters of the missile successfully.

The interface frictional conditions undergo transition when the operating conditions such as stresses, temperature, and sliding speeds vary. DMRL has done innovative efforts in this regard on a variety of materials including the Carbon–Carbon composites and Metal Matrix Composites. Through meticulous and extensive research, it was discovered that C–C based materials undergo a transition in friction to higher levels when the interface temperatures reach a threshold value. This knowhow helped in scientific analysis of the premature failures of C–SiC based jet vanes in missile systems. Subsequently, a composite coating comprised of a high temperature solid lubricant was developed to successfully reduce the friction by half. This contribution also resulted in the enhancement of the factor of safety in the jet vane designs by over 200%. These efforts by DMRL played a key role in the qualification of the rocket motor of an advanced missile system.

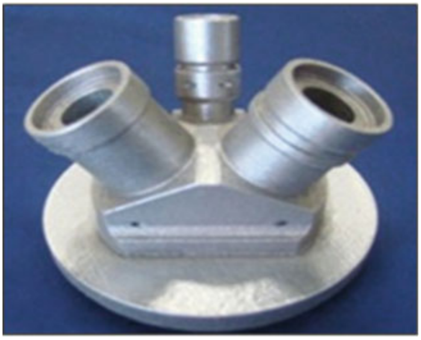
The components operating under hypersonic conditions are exposed to very high velocity gases and consequent heating to extreme temperatures, thereby experiencing considerable heat flux in excess of 200 W/cm^2. DMRL has developed a state-of-the-art test facility known as Induction Plasma Based Erosion cum Coating (IPEC) facility. This test infrastructure can thus facilitate the simulation of very high Mach numbers, high enthalpy, and high heat flux. This experimental facility at DMRL is truly unique, going by the global standards too.

15.20 Additive Manufacturing

Additive Manufacturing (AM) or 3D printing (3DP) is the process of generating a three-dimensional solid object, of virtually of any shape, from a digital model. A distinguishing feature of the additive manufacturing processes is that the material is added layer-by-layer in successive patterns to produce a component to its final desired geometrical configuration, to replace the conventional material removal methods. Coupled with phenomenal developments in allied fields such as Laser & EBM technology, CNC, Modelling & Simulation, and Powder Metallurgy; 3D Printing offers enormous potential for extensive applications in the development of complex components for defence.

Realizing the technological significance and future potential for Additive manufacturing, DMRL has been working in this area since 2008—especially applications to metallic materials using the LENS technology. Over the years, DMRL developed expertise in the metal additive manufacturing of advanced materials such as superalloys, stainless steels, Ti-6Al-4V, etc. Tensile mechanical properties of the LENS deposited metallic materials are found to be on par/superior to their wrought counterparts. Functionally Graded Material (FGM) panels of YSZ-IN625 materials were developed using LENS for hypersonic combustor liner applications. Thermophysical properties of these FGMs are found to be promising. The existing LENS-750 facility at DMRL is a 3-axis Directed Energy Deposition (DED) facility, where only relatively simpler shaped components may be generated. With the knowhow acquired in 3D Printing technologies, the development of a Fuel Nozzle component for Missile applications could be successfully accomplished by DMRL using the 3D Printing infrastructure at a collaborating agency. Innovative re-design of the component through appropriate modifications to its internal channels and manifolds enabled the development of 3D Printed unified assembly, without the need for support structures. Advantages realized through 3D Printing of the component include the assembly of 2 parts into 1, eliminating CNC machining & EB welding, and reducing material wastage.

The metal 3D Printing requirements of DRDO need to be addressed, offering end-to-end solutions together with complete process modelling, metallurgical, mechanical characterization, and qualification. Towards this objective, DMRL has embarked upon a project to develop different types of components, with widely varying sizes and complexities for defence applications, apart from the generation of standard alloy powders for 3D printing applications. Some of the major technological challenges identified to be overcome under this upcoming project include process development &standardization, process modelling of 3D printing for prediction of the properties, powder production technology for standard alloys, and qualification/certification methodologies for defence applications.



3D Printed Fuel Injector

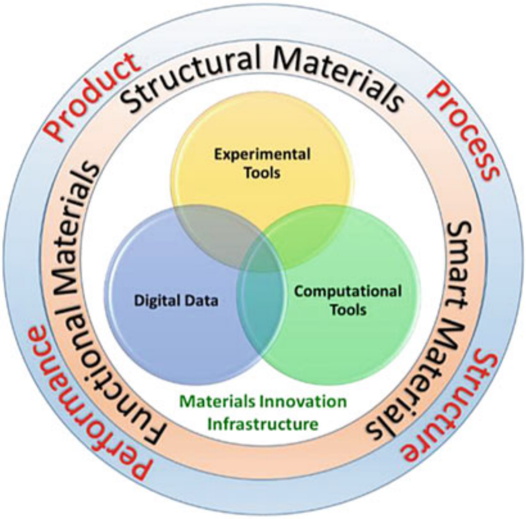
15.21 Outlook for the Future

DMRL developed numerous strategic materials/technologies with specific applications of interest to defence forces over nearly six decades of its service to the nation—the R&D at DMRL had direct applications in aircraft, ships, tanks, electronics, and missiles as well. Simultaneously, DMRL's scope of functioning continued to grow encompassing friction materials, heavy alloys for armaments, steel projectiles and armour, ultra-high strength low-alloy steel, titanium and titanium-base alloys, nickel-base superalloys, investment casting of superalloys for aircraft applications, magnetic materials, etc. Over the years, the laboratory has acquired a special status as a premier centre for R&D in metals, alloys, ceramics and composites. Currently, the multidisciplinary core competence at DMRL includes diverse areas such as product engineering, production support and performance analyses on metallic/alloy/composite parts, process development & surface engineering, Extractive metallurgy of Ti/Mg/Rare-earth metals, design & development of speciality alloys/intermetallics/ceramics/composites. The laboratory's efforts have resulted in significant contributions to DRDO Systems, the Tri-Services, and Civilian Spin-Offs. DMRL has also made a very prominent long-standing niche for itself in Failure Analysis support to the armoured forces, apart from several civilian spin-offs such as the development of turbine blades for energy applications and many bio-medical devices. DRDO's mission on the design, development, and manufacture of advanced hardware equipment for our Defence Services often rests heavily on the timely availability of tailor-made optimized materials. Responding to the call for self-reliance in materials and allied technologies, DMRL has undertaken numerous flagship programmes making significant advances in the concurrent development of futuristic materials and related processing/manufacturing technologies for defence applications.

The development of new materials/technologies is considered successful only when the concept is converted into a realistic product, and the same is deployed into service with adequate confidence on its performance. However, the developmental times are very long due to delayed stage iterations in the developmental cycle and complexities inherent to material systems. In order to keep pace with changes in design, it is inevitable to accelerate the development of materials. This can be achieved through emerging novel approaches such as *Artificial Intelligence (AI)*, *Machine Learning (ML)*, and *Integrated Computational Materials Engineering (ICME).* While the former two are essentially data driven, the latter can largely be based on physics-based models. More often, a judicious combination of all the above approaches is necessary for the accelerated development of optimized materials. ICME is a holistic way of seamlessly integrating materials development with the system's design. In other words, rather than being selected from the handbook/catalogue, material too becomes a design variable in the development of engineering systems. Therefore, materials are tailor-made for a specific application.

When the physical understanding on processing, material structure evolution and properties is at a mature level, several rigorous physics-based scientific models can be used to simulate the material behaviour. Each physics-based model can be visualized as a building block for ICME. Together with an appropriate integration platform, it is feasible to arrive at optimal materials solutions. Since ICME also includes performance models of the systems, it is in principle conceivable to solve the inverse problem of designer materials. Another complementary approach is based on application AI/ML techniques to operate upon databases. What is not comprehensible in terms of mathematical equations may be interpreted for inferences under the AI paradigm. With suitable structuring of data from multiple sources, an essential part of the material innovation infrastructure, digital data is created as illustrated in the figure below.

Since the curated data exists in the digital format, logical inferences may be drawn through ML using statistical algorithms and hence knowledge bases can be generated. Thus, mature AI systems can offer recipes to design newer materials in a very short time. A major breakthrough from adopting these approaches would be making materials' development keep pace with the design of engineering systems. Another aspect of AI is the design of intelligent experiments, based on prior data and autonomous reasoning of the cause-effect relationships.



Materials Innovation Infrastructure covers process-structure-property-performance data

15.22 Summary

DRDO's mission on the design, development, and manufacture of state-of-the-art hardware equipment for our Defence Services hinges on the timely availability of strategic materials. Ensuring self-reliance in turn mandates indigenous development of all materials. Responding to the call for self-reliance in materials and allied technologies, DMRL has undertaken numerous flagship programmes making significant advances in the accelerated development of futuristic materials for defence/ engineering applications.

DMRL has traversed through nearly six decades in time, contributing effectively to scientific efforts in addressing the present and future requirements of materials for defence applications. The laboratory has done consistently good in basic science, its scale-up to the technology level, and realization of commercial production for self-reliance as well. The focus all along has been to evolve holistic materials solutions for strategic applications, through seamless multidisciplinary team work. DMRL's thorough research for defence has resulted in commendable civilian spin-offs too. With ever increasing requirements for tailor-made materials and allied technologies for critical applications, DMRL is embracing the application of emerging disruptive technologies such as ICME/AI/ML for accelerated development of optimized materials/products.