KEYNOTE SPEAKERS

V Ramaswamy
PSG College of Technology, Coimbatore, India

Current Trends in the Usage of High Strength Steel for Line Pipe and Ship Building Applications

Of late there is a growing demand for use of high strength steels for different applications. This upsurge of interest has been brought about due to our increased understanding of the complex microstructures developed using sophisticated analytical instruments such as atom probe and high resolution. Transmission electron microscopy and EBSD. Steel makers also rose to the challenge by developing newer steel making techniques using secondary refining and Tundish metallurgy to produce required steel with cleanliness at affordable cost. Thus it has now been possible to produce strong high strength steels of varying yield strength and toughness. In this paper it is planned to outline the physical metallurgical principles involved in the development of micro alloyed steel using Thermo mechanical controlled processing followed by online accelerated cooling to produce target microstructures to control the properties. The steels developed for oil and gas transportation using the alloy design and improved processing have enabled to get yield strength level of 800 MPa and also having good toughness at -60OC. The different process adopted and the recent work on the development of X-100 grade line pipe steel will be outlined. A new microstructural engineering concept has been developed recently this has been based on identification of key microstructure parameters to which crack arrest length in full scale burst test can be related. Also to produce such microstructure in thicker gauge through alloy design of base chemistry and optimization of processing schedule. The processing of this steel and validation of this concept to prevent brittle cracks in actual field trials will be outlined. Work on heat treatment on line process (HOP) will be described and how this imparts high resistance to delayed fracture of a 32 min. thick Mn-Cr-Mo-V-steel will be outlined. Some of the current work on nanobainite and its applications will be discussed. Lastly mention will be made of indigenous efforts by steel makers to cater to the demands of various sectors such as ship building, oil and gas transportation, aerospace defence to produce the different grade of high strength steels having different yield strength needed for specific end use.

M R M Babu
Director, Advanced System Laboratory, DRDO, India

Advanced Materials for Missile System

K Muraleedharan
Director, CSIR-CGCRI, India

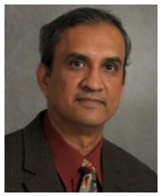
TBD

N K Mukhopadhyay
Indian Institute of Technology, BHU, India

Nanocomposites of Crystalline and Quasi Crystalline Phases Processes by Mechanical Alloying and Spark Plasma Sintering

Sanjay Sampath
Stony Brook University, USA

Structurally Integrated Damage Tolerant Coatings



Thermal spray coatings are used extensively for the protection and life extension of engineering components exposed to harsh wear and/or corrosion during service. Cermet coatings applied via high-velocity thermal spray are used in aggressive wear situations almost always coupled with corrosive environments. Despite their widespread use, the technology has lacked generalized scientific principles for robust coating design, manufacturing, and performance analysis. Advances in process and in-situ diagnostics have provided significant insights into the process–structure–property–performance correlations providing a framework-enhanced design. In this overview, critical aspects of materials, process, parametric and performance are discussed through exemplary studies on relevant compositions. The underlying connective theme is understanding and controlling residual stresses generation, which not only addresses process dynamics, but also provides linkage for both system (e.g., fatigue) and the surface (wear and corrosion) performance. This presentation will provide an overview these concepts structurally integrated coating design and remanufacturing of components.

Jürgen Hotz
ALD Vacuum Technologies GmbH, Germany

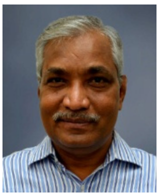
Technology Trends for Blades and Vanes

The demand for gas turbines is steadily growing since years and there is no indicator that this trend is going to end in the foreseen future. The main driver for the business is the aircraft industry which demonstrates with new engines 2 digit cost savings compared to the former models.

With the increased numbers of engines the demand for engine components e.g. blades and vanes is growing and for the existing engines the demand for spare parts adds to the business substantially.

Not only the excellent properties of latest super alloys are representing today the basis for the advances in turbine performance, but the combination of the best matching alloys, the reliable casting process and the best coatings.

The paper describes typical VIM configurations for alloy melting, casting technologies and the rapid development and success of the thermal barrier coatings. The paper will also show the successful story of ALD, installing VIM, precision casting furnaces and EB/PVD coating equipment at all important OEM’s over the last decades. A brief outlook into technology trends and how equipment can look like for the next generation will be given.



V S Raja
Indian Institute of Technology Bombay, India

Hot Salt Stress Corrosion Cracking of Ti-alloys

Hot salt stress corrosion cracking (HSSCC) is associated premature failure of rotating metallic components of aero and marine gas turbine engines. Among the various metallic materials, Ti-alloys are known to be very susceptible to such failure. A detailed investigation of the HSSCC behaviour of the Ti-6Al-4V, Ti-6242S and IMI 834 alloys, the former being a reference alloy, was done. Additionally, as these alloys were employed with fretting and abrasion resistant coatings and their performance was studied.

The slow strain rate tests showed that the alloys Ti-6242S and IMI 834 were susceptible to HSSCC at 300 °C and above, while Ti-6Al-4V showed its susceptibility at a lower temperature of 250 °C. In all these cases, the susceptibility increased with an increase in the test temperature. However, 1000 h constant load exposure tests of smooth tensile specimens did not lead to failure even at stress levels as close as 80% of their ultimate tensile strength although they showed significant loss in ductility in tensile tests carried out subsequent to constant load test. Pitting and thereby film damage, and the formation of slip steps have initiated the hot salt stress corrosion cracks. XRD analysis revealed formation of titanium hydride in the pit that seems to assist HSCC. Notably the loss in ductility occurred for IMI 834 and Ti-6242S alloys even when the unstressed hot salt exposed specimens were tensile tested. Contrary to them, Ti-6Al-4V alloy did not embrittle in such test conditions. The slow stain rate tests results showed that both the single layer (Cu-36Ni-5In) and bi-layer (Ni-5Al/Ni-25 graphite) coatings offered HSSCC resistance of IMI 834 alloy. Between the two, the bi-layer coating was found to be more effective in improving the HSSCC resistance characterized by a relatively smaller loss in the ductility as well as the extent of brittle attack. This observation has been attributed to the intact bond coat, which acted as a strong barrier for salt penetration.

K Bhanu Sankara Rao
University of Hyderabad, India

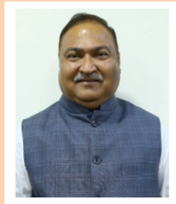
High Temperature Fatigue of Continuous SiC Fiber-Reinforced Titanium Alloy Matrix Composite

The characterization of strain controlled LCF properties of Metal Matrix Composites (MMC) is a challenging task, since there are no guidelines whatsoever on the specimen geometry, machining to be adopted, surface finish, the method of attaching thermocouples to the gauge section and the type of extensometry that has to be adopted. These problems have been solved successfully and developed procedures for conducting fully reversed tension-compression fatigue tests on continuous SiC fiber reinforced Ti-15-3 MMC at high strains. Methods have been developed for characterizing sub-structural changes that occurred during LCF testing in the in-situ matrix of the composite by transmission electron microscopy. In situ matrix deformation and precipitation in continuous fiber reinforced MMC's have been found to be heterogeneous. The modulus changes of the matrix material and the composite during cyclic deformation have been used to determine the onset of precipitation. Through TEM studies, the sources of crack initiation in MMC's have been established. An overview of the salient features pertaining to in-situ precipitation, deformation and fracture behavior of the MMC under load and strain controlled LCF conditions will be addressed.

Arvind Kumar Agarwal
Senior Deputy DG, Ordnance Factory Board, India

Future Trends in Defence Materials on Ordnance Factory Perspective

Dinesh Kumar Likhi
CMD, MIDHANI, India



Self Reliance in Strategic Sectors: Myth and Challenges

Rajkumar P Singh
Kalyani Center for Technology and Innovation, Pune, India

Achieving Outstanding Gun Barrel Performance by R & D and Future Challenges in Defence Sector

Barrel is the heart of any Artillery Gun. It is a long lean cylinder that carries out several roles, such as safely handling high pressure combustion gases and offering a right direction to the projectile in the intended path. Gun Barrel internal bore experiences complex conditions during firing. Major failure modes are erosion, wear, fatigue, Permanent Bore Expansion and Barrel Wall Rupture. These conditions are mainly created due to high pressure hot propellant gas attack. The Permanent Bore Expansion, Gas Leakage and Bursting can be mitigated by proper design and material selection for the Gun Barrel. To design and develop a Gun Barrel to overcome these failures is a challenging task for any artillery gun manufacturer. The barrels are designed to provide maximum resistance to fatigue, erosion and wear. Due to hundreds of firing, formation of micro cracks take place on the internal surface of the barrel. These micro cracks propagate and coalesce and in due course can be the reason of failure. The still bigger cause of failure is undesirable material loss occurring on the bore surface caused by the passage of hot propellant gases, which leads to thermal chemical and mechanical interactions leading to erosion and degradation of material. Wear takes place due to mechanical degradation. While in use, the barrel is exposed to harsh conditions, such as short and cyclic intervals of temperature rise [over 1000˚C] and a high pressure pulse in the harsh environment of propellant gas combustion.

To overcome the above severe service conditions, the gun barrels have to be made with proper chemistry of steel and have to undergo appropriate heat treatment cycles to get the desired micro structure to provide the right properties. To reduce erosion and wear, surface characteristics of the barrel can be improved by surface treatment or coating. Steel alloyed with alloying elements like Si, Cr, Mo, V, Ni, etc. are generally selected. AISI 4330 V (Ni-Cr-Mo-V) has desired properties if subjected to proper heat treatment. The present paper deals about achieving the desired mechanical properties, using such steel and providing right heat treatment. Experimental results of the barrel material under simulated pulse pressure shocks have been discussed. Comparative performance results with surface treatment and different types of coatings on wear and erosion behavior of barrel is also presented.

In this presentation, some other challenging areas in the Defence Sector like development of Improved Bomb Shell, Unmanned Ground Vehicle, Unmanned Ariel Vehicle, Tank Wheels and Protective Armours have been covered in brief, indicating desired direction for future research.

Qiang Wu
ALD Vacuum Technologies GmbH, Germany

VIGA and EIGA Gas Atomization Systems for Production of High-Quality and Spherical Metal Powders

VIGA (Vacuum Induction Melting Inert Gas Atomization) and EIGA (Electrode Induction melting Inert Gas Atomization) Systems made by ALD are utilized worldwide since 1970sfor producing large amounts of high-quality and spherical metal powders. Nowadays, the demand for high quality metal powders is sharply increased, mostly driven by Additive Manufacturing (AM) and Metal Injection Moulding (MIM). ALD as leading key supplier not only keeps the existing high quality level of its gas atomization equipment, but also improves techniques and implement new features for better process tuning to tailor powder characteristics, improve and optimize powder morphology and fine powder yield, reduce gas consumption and lower production cost.

This presentation provides an overview of the state of the art VIGA and EIGA systems, the leading methods to produce large amounts of high-quality metal powders with properties that are optimized for downstream processing. Furthermore, the VIGA and EIGA systems are reviewed in detail with respect to powder yield, d50 value and particle shape. For R&D purpose, an VIGA2B-EIGA dual system enables to produce a huge variety of metal powders within one system both for conventional alloys like Fe, Ni, Co, Cr (VIGA mode) as well as for reactive and refractory alloys like Ti, Zr, Nb, Ta and precious metals (EIGA mode).

R Banerjee
University of North Texas, U.S.A.

Precipitation Strengthened High Entropy Alloys or Complex Concentrated Alloys

While high entropy alloys (HEAs), based on single phase concentrated solid solutions, have attracted a lot of worldwide attention, their potential application as real engineering alloys is rather restricted, especially for high temperature applications. Furthermore, often the experimentally observed single phase HEA is the result of second phase precipitation constrained by thermodynamic and kinetic factors. This presentation will focus on designing HEAs strengthened using a second (or more) phases. Al0.3CoCrFeNi will be discussed as a model HEA, to investigate second phase precipitation as a function of different thermo-mechanical treatments [1-5]. This includes refined L12 (γ') precipitation as well as B2 precipitation in this alloy leading to substantial improvements in yield and tensile strength while maintaining substantial ductility [1,2]. Subsequently, using a CALPHAD based solution thermodynamic approach, another novel precipitation strengthened *fcc* based HEA has been developed with the objective of maximizing the phase fraction and solvus temperature of L12 (γ') precipitates. Detailed microscopy using transmission electron microscopy (TEM) and atom probe tomography (APT) was carried out to characterize the alloy in various conditions. Hall-Petch strengthening coupled with precipitation resulted in high tensile yield strength of 1600 MPa with a reasonably good ductility of ~15%. These results hold promise for the development of precipitation strengthened HEAs for high temperature applications.

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Manoranjan Patri
Naval Materials Research Laboratory, DRDO, India

Advanced Materials for Power and Energy Systems: Fuel cells and Supercapacitor

In recent years, green and renewable energy systems have become the central area of research worldwide owing to the rapidly depleting fossil fuel reserves and environmental concerns. In order to cater to the ubiquitous power and energy requirements, indigenous technical knowhow is crucial for India's energy security. Fuel cells (FC) and supercapacitors are being considered as the next generation power generating systems due to their high efficiency and low environmental impact. NMRL, with a flagship FC based Air Independent Propulsion (AIP) programme, is at the forefront of research on power and energy devices viz. fuel cells and supercapacitors. NMRL aims to develop affordable power solutions for surface combatants, submarines and warships, with potential civilian spin-offs through these alternative energy sources. A FC is like a battery, which generates electricity from an electrochemical reaction. However, unlike batteries, FCs can run indefinitely by using an external supply of chemical energy through hydrogen and oxygen/air. R&D effort at NMRL is focused on four types FCs viz. Phosphoric acid (PAFC), High Temperature Polymer Electrolyte Membrane (HTPEMFC), Solid Oxide (SOFC) and Marine sediment (MSFC). This highly interdisciplinary research at NMRL encompasses the entire scope associated with development of stable and high performance devices. It includes electrode and electrolyte material selection, optimization of multiple processes, structure-property correlations, unit cell evaluation, failure analysis, up scaling, stack design and assembly, operation protocols and endurance studies. This paper highlights the above issues and the technology readiness levels (TRL) of each of these FC technologies with particular emphasis on the specific material aspects and the differences in their basic working principles. The unique features and challenges associated with the NMRL patented materials and processes used for each technology will also be elucidated with an overview of operating temperatures, reactions and their respective advantages and disadvantages.

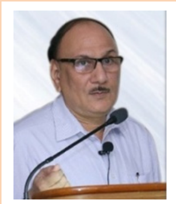
Some of the NMRL patented materials technology for various fuel cell technologies includes (a) porous conducting carbon paper (b) graphite based heat exchange plates (c) high temperature polymer electrolyte membrane (d) corrosion resistant catalyst for PAFC and (e) novel process for onboard hydrogen generation.

Supercapacitors, on the other hand, are high energy density electrochemical charge storage devices which can provide pulse power through rapid charge and discharge cycles. NMRL has developed supercapacitors with capacitances ranging from 30 to 1600 F with maximum voltage of 2.7. The internal resistance, which is the critical factor for high cycle life of a supercapacitor, has been minimized to 30±5 mΩ for 30 F and 1 mΩ for 1600 F supercapacitor, comparable to the state of art. Supercapacitors modules having high voltages such as 2.5 F-30V, 63 F-125V are being developed for multifarious defence applications such as missiles, rail guns and NMRL developed AIP system. The NMRL patented material and its processing techniques towards fabrication of supercapacitors with high cycle life and lower internal resistance will be presented in detail.

R K Ray
IIEST, Shibpur, India

Texture, Microstructure, Grain Boundary and Internal Stress

A great majority of materials scientists and engineers is primarily engaged in designing polycrystalline materials with pre-assigned properties. It has been known for a very long time that any property of a material is very much a function of its microstructure. Since in most cases microstructure of a material cannot be revealed with the naked eyes, and since "seeing is believing", the great science of microscopy was developed. In general terms, a microscope is an optical system which transforms an "object" into an "image", usually making the image much larger than the object. There was a time when the only characterization tool to study materials property used to be primarily microscopy. The science and art of microscopy have seen a sea change over the years and the scientific community has, at its disposal, some of the highly sophisticated tools, which are simply mind-boggling. Over the years, however, it became quite apparent that microstructure alone cannot explain property in its totality. In many instances, the preferred grain orientation or crystallographic texture of a polycrystalline material can add value to microstructural observations in a major way towards explaining a material property. Many experimental results also point to the fact that in addition to microstructure and texture, the nature and distribution of grain-boundaries as well as internal stress within a material may also play a very important role in determining the properties of a material. In this presentation, a number of examples will be cited to show the inter-relationships between the four parameters, namely, microstructure, texture, grain boundary distribution and internal stress, which ultimately shape the property of a material.



Raksh Vir Jasra
R & D Centre RIL, India

TBD

G K Dey
Homi Bhaba National Institute, BARC, Mumbai, India

Development of Advanced Materials for Application in the Nuclear Energy Sector

Development of alloys for the nuclear sector holds special challenges as the requirements are very stringent. The properties have to be of the highest order as these alloys have to see very hostile environments like presence of radiation for many of the applications. These also necessitate very long life as replacing these radio-active components poses other restrictions. Very long life of the components under these very hostile environments calls for very high creep resistance and corrosion resistance.

The story of indigenous alloy development happens to be more challenging as many of the metals in this sector are under embargo and cannot be imported. The first activity, therefore, is to locate the deposits of ores of these elements in the country. This activity is followed by developing the flow-sheet for extraction of these elements from Indian ores. Based on lab scale production, flow-sheet for plant scale production is created. Indian scientists have gone through all these different stages and successfully established the whole supply chain for many of these elements making the country fully self reliant. This presentation first gives a flavor of the aforementioned activity of element extraction from Indian resources. This is followed by description of the alloy development strategies for indigenous alloy development. The last part of the presentation gives an account of the performance of these alloys. All along the need for basic research in each of the domains to create our own knowledge bank has been highlighted.

Dinesh Srivastava
Chief Executive, Nuclear fuel Complex, Hyderabad, India

Manufacturing of Materials for Thermal Nuclear Reactors

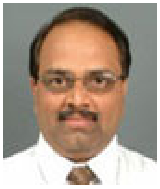
Nuclear Fuel Complex (NFC), one of the constituent units of Department of Atomic Energy (DAE), was established at Hyderabad during early 1970s.NFC has mandate to develop and manufacture structural components and fuel assemblies required for all the operating Nuclear Power Reactors as well as future advanced reactors, in the country. The Complex is engaged in the manufacture of various Zirconium alloy reactor core structurals like Pressure Tubes, Calandria Tubes, Garter Springs, Reactivity Mechanism Assemblies for the Pressurized Heavy Water Reactors (PHWRs) and Square Channels for the Boiling Water Reactors (BWRs). The type of structural elements varies with different types of reactors i.e., PHWR, BWR and the Breeders etc.

The expertise gained in manufacturing Fast Breeder Test Reactor (FBTR) sub-assemblies was successfully translated to develop technologies required for manufacturing core sub-assemblies and components required for the forthcoming 500 MW Prototype Fast Breeder Reactor (PFBR) at Kalpakkam, Tamil Nadu.

NFC also manufactures a variety of seamless tubes for strategic applications to meet the requirements of DAE, Space and Defence. NFC being multi-disciplinary center; it provides excellent opportunities for metallurgical, mechanical and other engineers to be associated with processing and manufacturing of technological challenging materials and their components.

Amarendra K Singh
IIT Kanpur, INDIA

Designing Workflow for Vertical Integration of Models of LF Operation



The main purpose of LF operations are temperature and composition control. LF operation with facility for arcing is used for temperature control. Composition control involves refining and alloying through additives such as deoxidizers, fluxes, alloying agents, inclusion and slag modifiers, etc. Argon purging is an important operation in LF to promote thermal and chemical homogenization and accelerate process kinetics. Quality of steel is linked to all the sub-processes of LF operations.

In the framework of ICME, product specifications at the end of LF operation are dictated by the requirements of downstream operations and are obtained through horizontal integration of models. The ability of ladle furnace to meet these specifications is dependent on incoming raw materials and process and design set points of LF operations. The quality of liquid steel is governed by multiphase / multi-scale fluid flow, heat transfer, mass transfer, thermodynamics and kinetics of chemical reactions, etc. Depending on the governing physics, various CFD based models, and thermodynamic and kinetic

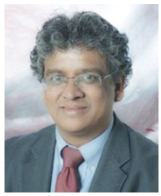
models of sub-processes are required. These sub-models were either developed or were taken from the existing literature and were integrated to relate the quality of steel with various sub-processes.
The model integration of LF process involved linking of individual surrogate models (obtained from CFD or other models) to facilitate information flow across sub models and designing workflow for the optimization framework. Some key results obtained through the vertical integration of models will be presented in this talk.

G Padmanabham
Director, ARCI, Hyderabad, India

Aditive Manufacturing of Aerospace Components

Sundar V Atre
University of Louisville, USA

Processing with Powders: From Powder Metallurgy to Additive Manufacturing



Two major challenges need to be addressed in translating a preliminary engineering design problem into a disruptive commercial product based on advanced materials and systems: i) materials that will deliver multiple functionalities, and ii) processes that will integrate the materials into a highly intricate product shape. These challenges are highly inter-related, and understanding the nature of these inter-relationships are crucial to the successful development of new applications. The primary focus of our research is the design and manufacturing of multi-scale architectures using a broad range of materials. This presentation will explore the use of particulate materials in the context of net shaping processes, and applications associated with additive manufacturing, popularly referred to as 3D printing. This presentation will emphasize transportation and medical applications in the manufacturing space based on our research and teaching at the University of Louisville

Rahul Mitra
Indian Institute of Technology, Kharagpur, INDIA

Effect of LaB_6 Addition on Densification and Compressive Creep Behavior of Spark Plasma Sintered ZrB_2-SiC Based Ultra-High Temperature Composites

A study has been carried out to examine the effect of LaB_6 addition on the densification and compressive creep of behaviour of ZrB_2-SiC composites processed by spark plasma sintering (SPS) at 1600 or 1800 ^{o}C. ZrB_2-SiC composites with varying amounts of LaB_6 (7, 10 and 14 vol.%) have been prepared by SPS at 1600 and 1800 °C under applied ram pressures of 50 and 70 MPa, respectively. The relative density has been found to increase with increasing volume fraction of LaB_6, which acts as oxygen getter during sintering. The 14% LaB_6 composite has shown relative densities of >99% and ~98.2% on SPS at 1600 and 1800 ^{o}C, respectively. Interestingly, higher densities have been obtained at 1600 ^{o}C than that at 1800 ^{o}C. The densification mechanisms during SPS have been analyzed on the basis of Bernard-Granger model for both the sintering conditions. Under isothermal and isobar conditions, the stress exponent (n) ~5-6 suggests the activation of dislocation-based mechanism in all composites at 1600 ^{o}C. However for sintering at 1800°C, n~2 for the composites with 7 and 10 vol.% LaB_6 indicates that a diffusion-based mechanism aided by grain boundary glassy phase formation is operative, whereas n~3 for that with 14 vol.% LaB_6 is suggestive of dislocation creep. Furthermore, compression creep tests on the aforementioned ZrB_2-20 vol.% SiC-(7, 10 or 14 vol.%) LaB_6 composite samples at 1300^{o}C under stresses between 47 and 78 MPa, have exhibited the lowest steady state creep rate in case of the composite with 10 vol.% LaB_6. The stress exponents obtained for creep of composites having 10 vol.% LaB_6 (~1.3±0.1) and 14 vol.% LaB6 (~2.6 ± 0.2) suggest respectively, diffusion and dislocation glide as operating mechanisms. Grain boundary sliding promoted by finer grain-size and interfacial glassy phase, causes damage by inter-granular cracking. The oxide scales formed during creep exhibit more cracks and grow thicker than those by isothermal exposure at 1300^{o}C for the similar duration.

N Eswara Prasad
Director, DMSRDE, DRDO, India

Materials and Materials Technologies for Indian Defence Products, Prototypes and Systems

Defence materials and materials technologies are not only numerous but also widely ranged and most challenging. In this talk, an attempt will be made to elucidate various materials and materials technologies developments for some of the most critical products, prototype and systems of Indian defence:

A. **Products:** 1. Jet Fuel Starter (JFS) Castings; 2. Turbine Blades and Vanes Investment Castings for Kaveri Engine; 3. Antenna Platform (APL) castings for the MMRs of LCA-Tejas; 4. Ti Alloys for LCA, LCH, AMCA and Aero-Missiles; 5. Half Alloy Tubes; 6. FSAPDS – I & II; 7. C-C Brake Discs; 8. Naval Steel Plates, Sheets, Bulb Bars & Weld Consumables; 9. Composite Armour for LCH and MI-17; 10. CBRN Products - Suits, Boots, Haversacks; 11. Bio-Sensors & Detectors; 12. Technical Textile Products – Glacier Clothing, especially ECW Products; 13. Camouflage Products – MCS, MSPCE, RSCN, etc.; 14. Laser Dazzlers; 15. Passive Night Vision Goggles, 16. Radars; 17. LIDARS etc.; 18. Single Source Precursors for AlGaN/GaN Devices; 20. Wave Tubes etc.; 21. Bio Foods; 22. Bio Medical Products; 23. Bio Toilets and 24. Bio Digesters etc.

B. **Important Prototypes:** 1. Personal Protection Systems – BPJs, Helmet, BAMI; 2. Air Intake Ducts for Aero Systems; 3. Leading Edges for Aero Systems.

C. **Major Systems:** (A) AERO SYSTEMS – LCA, LCH and Variants; 2. AEW&C; 3. Aero Missiles (Nirbhay, ASTRA & HELINA), 4. UAVs – Nishant, Rustom; Micro and Mini UAVs, 4. Gas Turbine Engines (Kaveri & its Variants), 5. Aero Stats (Nakshatra); (B) MISSILE SYTEMS –1. Surface to Surface: Prithvi; Dhanush, QR SAMs, 2. Surface to Air: LR/MR/QR/SAMs, 3. Air to Air: ASTRA & NGARMs, 4. Ballistic: Agni I-V, BrahMos Cruise Missiles and its Variants, 5. Aerial Smart Bombs (Garuda & Garuthma); (C) NAVAL SYSTEMS –1. HAMSA, 2. ABHAY, 3. USHUS, 4. VARUNASTRA, 5. SAGARDHWANI, 6. AIP; (D) COMBAT SYSTEMS –1. MBT ARJUN I & II, 2. Muntra – N; (E) ARMAMENT SYSTEMS –1. Pinaka & 2. Small Arms; (F) ELECTRONIC SYSTEMS - 1. INS; 2. OBC; 3. ECMs; and, 4. ECCMs (G) CAM SYSTEMS–1. ADSS, 2. SAMAR & 3. Surveillance; (H) MATERIAL SYSTEMS–1. NBC; 2. Water Purification; 3. Armour; 4. PPSs.

In addition to the above, various materials programmes of DRDO and several important national initiatives, programmes and policies will also be briefly described.

Seema Vinayak
Director, SSPL, DRDO, India

A Glimpse of Material and Device Technology at SSPL

G Madhusudhan Reddy
DMRL, DRDO, India

Joining of Advanced Materials

Bhanu Pant
VSSC, ISRO, Trivandrum, INDIA

Evolution of Materials Technology for Indian Space Program

The use of Space technology is ever increasing in the field of Communication and in Remote Sensing for earth observation for societal purposes and for Surveillance. Also, various Science Missions to explore outer space are being undertaken by Space faring nations including India. These Space programs require a variety of materials for use in diverse and demanding environments. Based on the applications, the material requirements can be categorized broadly into structural (or load bearing e.g. launch vehicle/ spacecraft structures and pressure vessels) and functional such as for thermal protection, magnetic, electronic, controlled porosity seals and bimetallic adaptors. As Indian Space launch vehicle program evolved from SLV through PSLV, GSLV, GSLV-Mk3 and presently to Gaganyaan, there has been huge demand on development of technologies for both of these types of materials. There have also been technology demonstration missions like Space Recovery Experiment (SRE) involving re-entry and recovery. This has led to spurt in material and process developments both in terms of complexity and size. Added challenge has been the demand of productionization of most of the structural materials and processes in a regular and reliable manner to cater to large number of launch missions.

To start with ISRO had modest solid propulsion technology in SLV and ASLV which graduated to liquid propulsion in PSLV and then to Cryogenic for GSLV and GSLV-Mk3. Recently Semi-cryogenic engine development using LOX and Kerosene combination has given new challenges in materials and special coatings. New assignment of Gaganyaan needs totally man-rated launch vehicle and also systems for man specific needs. This has further expanded the material and system requirements.

The Indian journey of space materials has been based on lab-to-industry-to-launch concept and driven by the programmatic needs. Over the years Maraging steel, Al alloys, Ti alloys have been successfully indigenized and are being processed in required sizes, quality and numbers. Associated secondary processing of components by closed-die forging, hot forming, pilgering, investment casting and joining of similar/ dissimilar metal/ metal-ceramic joints by TIG, EB welding, friction welding, explosive bonding and diffusion bonding has also been established. Newer initiatives to melt/ forge/ roll/ ring roll and friction weld the high specific-strength Al-Li alloys have also been taken for future missions. In the area of ceramics; Silica tiles for re-entry missions, Silica aerogel for launch vehicles/spacecrafts, BN-SiO2 composite / porous- W for electric propulsion are some of the new developments. Further, there has been good amount of work on metal-to-ceramic hermetically sealed joints for Li-Ion terminal seals. All these developments are carried out in-house as well as in collaboration with external institutes and subjected to stringent qualification tests for induction into Space programs.

In the present paper, an effort has been made to present an overview of the material and process developments of Indian Space program to meet the growing launch vehicle missions both in terms of size, complexity and numbers.

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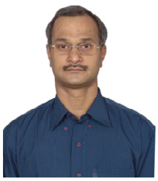
TBD



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Fatigue and Fracture Behaviour of Cu-Strengthened Naval Steel

For the evaluation of integrity of structural components as per current codes for engineering critical assessment, it is imperative that fracture mechanics based characterization of the stability and growth of flaws be carried out. Some interesting observations on the fatigue and fracture behaviour of two varieties of naval steels are presented in this paper. Innovations in test and analysis procedures that may be implemented in order to obtain meaningful information from fracture mechanics based characterization programmes are also highlighted.

The data presented pertain to fracture mechanics based characterization of primarily two Cu-strengthened HSLA steels, namely HSLA-80 and HSLA-100, used for naval structural applications. Extensive corrosion fatigue crack growth tests (C-FCGR) had to be carried out to understand the effects of mean stress, frequency of loading, environment chemistry and cathodic protection on crack growth and crack closure behaviour. Since C-FCGR tests are required to be conducted at low frequencies in order to permit corrosion mechanisms to influence the crack growth, the tests were necessarily of extremely long duration. Experimentally this posed a challenge. A decreasing ΔK test procedure that accelerated the test considerably, especially for high strength materials such as the Cu-strengthened steel, was therefore developed and validated for use.

For fabrication of naval structures with the Cu-strengthened HSLA steel, heat treated steel plates are customarily cold deformed and welded together. The microstructural conditions employed do not permit post-deformation heat treatment to relieve stresses, and the welding procedures are designed accordingly. This called into question the validity of using fracture toughness values determined primarily on undeformed conditions for design. The effect of cold deformation on fracture toughness was therefore determined, and it was observed that, contrary to conventional wisdom, the fracture toughness is retained at its original level for lower levels of cold deformation. A model was developed to explain the retention of fracture toughness that employed essentially tensile deformation material parameters, and it was shown that the model could predict the experimental behaviour quite accurately.

The stretch zone that precedes the initiation of ductile fracture has assumed considerable importance in the determination of fracture toughness in ductile materials used for structural applications. The Japanese standard on fracture toughness has incorporated it, while the European procedure for fracture toughness evaluation is actively considering its inclusion. It was instructive to examine the formation of the stretch zone during fracture of the Cu-strengthened HSLA steel. It was observed that the stretch zone depth, and not the stretch zone width, showed a better correlation with the trend of variation of fracture toughness with cold deformation. Formation of secondary cracks, however, results in mismatch of the energy expended in its formation.

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Multi-Functional Materials for Alternative Energy / High Performance Devices

Functional materials are on demand for many energy related applications. The functional materials viz. magnetic materials, battery materials, thermoelectric materials, and Fuel cells form important components for energy saving devices in automotive, and strategic sectors. Current research on functional materials demonstrate that well designed process -microstructure strategies for tuning the properties are essential to meet the demand at device or system level. By processing magnetic materials to nano size, the interaction between magnetic length scales and micro structural length scales controls the properties. By virtue of large utilization of magnetic materials in many electro-technical devices (aerospace, Electric vehicle sectors) , where the quantum of requirement is increasing day-by-day, there is a pressing need for the development of the materials with high performance not only to minimize the cost; but also to enhance the energy saving. In recent times, the progress in Li-ion battery technology, especially among the electrode materials for high charge / discharge capabilities, is a great boom to Electric Vehicle / Hybrid electric vehicle sectors and also for strategic areas. One of the concerns with battery electrode materials is on how to enhance its specific capacity / energy density and this demands development of innovative process for new chemistry. Yet another energy saving systems are based on thermoelectric energy generators (TEG) and are gaining significant importance as they do not involve any mechanically moving parts and thus assuring high reliability along with noiseless operation. TEG can be operated over a wide temperature range. The enormous amount of heat being lost from power plants, factories, vehicles, and residential homes offers a great opportunity for making direct use of this energy. In many energy systems – such as automotive wherein a direct conversion of heat flows into electrical power allows for a reduction of fuel consumption and thus for a sustainable protection of the environment. Our Lab (ARCI) focuses on developing such high performance functional energy saving materials for industrial trails and technology demonstration / transfer. This presentation will focus in detail on those functional materials (hard / soft magnets, magneto-caloric materials, thermoelectric and battery materials) and their process-structure-property correlation investigated for sustainable energy applications. Specifically, the impact of these materials on automotive sector and aero space sectors will be highlighted.

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Characterization of Intrinsic Fatigue Thresholds for Additive Manufactured Materials

A generally accepted consequence of additive manufacturing in contrast to conventional processes is the increased probability of defects by way of porosity and disbond. From a Fracture Mechanics viewpoint, these constitute pre-existing cracks whose growth under service conditions will be governed by threshold conditions of fatigue crack extension. ASTM E647 describes standard practice for characterization of threshold stress intensity. Recent research has shown that ΔK_{th} obtained by this method do not reflect potential material response under conditions of service loading for two important reasons. Thus, values obtained by standard practice may include a substantial component of crack closure that results in inflated values of ΔK_{th}. This distorts assessment of intrinsic local fatigue resistance as affected by actual near-tip residual stress conditions. Obviously, the conditions of growth of initial defects in additive manufactured conditions may be different from those reproduced by prevailing standard test practice.

Refs [1,2] describe procedures to establish the unique relationship between a certain intrinsic K_{th} and near-tip residual stress, σ^* that reflects threshold fatigue resistance under closure free conditions. This relationship permits improved engineering estimates of residual fatigue life under service conditions that require the ability to account for load history effects. In the case of additive manufactured materials, it is likely to provide valuable information on K_{th} that may be more appropriate to apply to engineering design of components for safe life in the presence of internal defects progressing in high vacuum.

From the close connection between crack-tip diffusion kinetics and intrinsic fatigue resistance it would follow that the high end K_{th} values associated with compressive σ^* values may be close to values likely to be seen by internal defects that essentially are stressed in high vacuum, while the low end K_{th} values are likely to characterize intrinsic fatigue resistance of surface defects exposed to atmospheric influence. These inputs are likely to assist fatigue life estimates for components and also managing tolerances on technologic process parameters associated with additive manufacturing of individual components.

Work is in progress on characterization of the K_{th} versus σ^* relationship for additively manufactured specimens from a steel, Al-alloy and nickel-base superalloy. The programme is adapted to miniature C(T) coupons to suit requirements of additively manufactured coupons and component extraction.

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Hot Cracking Susceptibility of Candidate USC/AUSC Boiler Materials

With the objective of improving efficiency and reducing carbon emission, new fossil base power plants with improved design and high operating temperatures and pressures are being constructed worldwide. Among these Ultrasupercritical (USC) plants are already in operation in many countries including India while Advanced Ultrasupercritical (AUSC) plants are in final stages of design and prototype testing. In India, design and construction activities for an indigenous AUSC plant is being led by a consortium consisting of M/s BHEL, M/s NTPC and IGCAR, Kalpakkam. While ferritic steels are the major material of choice for most of the conventional power plant components, in USC and AUSC plants austenitic steels (304HCuSS and Sanicro-25) and Ni base alloys (Alloy 617 and Alloy 740) replace ferritic steels for many of the boiler and turbine components. As welding is an important fabrication process during construction of power plant components, weldability is an important consideration in the selection of these materials. Being fully austenitic these new alloys are prone to hot cracking during welding. Hence susceptibility of Alloy 617, 304HCuSS and Sanicro-25 to hot cracking was studied using varestraint test and "GleebleTM" based hot ductility tests. The hot cracking sensitivity of the alloys increases in the order: Alloy 617M< SS 304HCu< Sanicro-25 respectively. The reasons behind the hot cracking behavior exhibited by these alloys were investigated thoroughly using various characterizations tools on the tested specimens. The results of the investigation showed that constitutional liquation of Nb-rich phases in the heat affected zone during welding was responsible for hot crack formation in these alloys. The results of the study show that the susceptibility of these candidate AUSC alloys can be ranked from moderate to highly susceptible for hot cracking. These results could be correlated with hot cracks observed during welding trials carried out on the boiler tube produced from these materials and would be useful while fabrication of the boilers for the USC/AUSC plants.

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Six Decades of Macro-mechanics of Composite – A Personal View

The three dimensional (3D) modelling of laminates with a large number of orthotropic/isotropic layers becomes intractable [1-4]. Researchers, therefore, focused their attention on two dimensional (2D) analytical models coupled with effective, general and robust computational tools. As a rule, 2D smeared single-layer theories/models [5-8] dominate the scene. The basic behavioural difference between a laminate and a homogeneous structural element lies in the significant contribution of transverse shear and transverse normal energies in structural elements' deformation in the former. In an effort to improve the physics of the behaviour, most of the analytical models rely on some a-priori assumed through thickness distribution for the unknowns: displacements or strains or stresses.

Classical Lamination Theory (CLT)

The CLTs for composite beams, plates and shells is an extension of the Euler-Bernoulli beam, Poisson-Kirchhoff plate and Love shell theories, respectively. These neglect the effects of transverse strains and assume each lamina (sheet) to be in a state of plane stress. CLT fails to predict accurately the static and dynamic response in case of laminates which are rather thick and/or even thin but exhibit high anisotropy ratios. Pister and Dong [9] are the pioneers in extending the theory of Poisson-Kirchhoff to laminated plates [10].

First Order Shear Deformation Theory (FOST)

Reissner [11] and Mindlin [12] are the pioneers in including effects of transverse shear energy in homogeneous plates; the former used an assumed stress based approach while the latter used the popular assumed displacement based approach. These theories/models assume that transverse normals, which are originally straight and perpendicular to the mid reference plane/surface, remain straight but not necessarily normal to the mid reference plane/surface during deformation under applied loads. The major disadvantage of the FOSTs is that they cannot correctly represent the through thickness distribution of the transverse shear deformation (strains). They also require shear correction coefficients to correct the corresponding strain energy terms and these coefficients are not easy to obtain for laminates/sandwiches. An application of FOST for thermal buckling analysis is shown by Babu and Kant [13].

Higher Order Shear-Normal Deformation Theories (HOSTs)

Here, the through thickness distribution of the displacement functions are assumed to be higher order polynomials of the thickness coordinate. Such an assumption overcomes some of the disadvantages of the FOSTs. Hilderbrand et al. [14] pioneered such an approach. Quadratic, cubic and/or higher degree polynomials have been systematically described, used and referenced [15-19]. The models of Levinson [20], Murthy [21] and Reddy [22] are similar except that Reddy derived variationally consistent equilibrium equations. Unfortunately this model requires C1 continuity of the displacements. Kant [23] and his co-workers pioneered a C0 displacement finite element (FE) basis of higher order displacement models. Finite element and closed-form solutions to laminate and sandwiches under thermal loading have been attempted in Babu and Kant [13], Kant and Khare [24] and Khare et al. [25] and closed-form solutions under mechanical loads, for the first time, were obtained by Kant and Swaminathan [26-30].

Transverse Interlaminar Stresses

During the last few decades, many publications are reported in the literature on the use of various 2D theories for the stress, free vibration and buckling analysis of laminated composites and sandwiches. Both analytical and FE models are used for the analysis. Most of the work is confined to validating the accuracy of results obtained using a particular model by comparing the results with the available 3D elasticity solutions. However, in the displacement based analytical/FE approaches, the inplane stresses are first computed in the first phase and the transverse interlaminar stresses are then estimated by integrating 3D equilibrium equations of elasticity along the laminate thickness in the second post-processing phase and there are serious limitations of this approach. The estimates are not only inaccurate but the methods are unreliable and the whole methodology lacks robustness. The root cause for this situation lies firstly in the mathematical model for the integration of the transverse shear stresses. The mathematical models are improperly posed boundary value problems (BVPs) and secondly the error propagation in the numerical evaluation of the high derivatives of displacements. Therefore, accurate and reliable evaluations of the transverse stresses have not been addressed adequately [31-33] in the developed approached to the date.

Partial Discretization Methodology

Significant contributions have been made in the development of direct numerical transient analysis procedure in the last three decades. Most of these procedures are based on semi-discretization methods in which the space dimension is discretised by the FE method. Such a strategy transforms the governing system of partial differential equations (PDEs) to a system of ordinary differential equations (ODEs) in time.

An attempt is made here to extend this methodology to elastostatic problems ranging from 3D solids to 2D plates and shells to one dimensional (1D) beams and arches and whose behavior is mathematically formulated as a two-point BVP governed by a set of liner first-order ODEs.

$$\frac{d}{dz}\mathbf{y}(z) = \mathbf{A}(z)\mathbf{y}(z) + \mathbf{p}(z) \qquad (1)$$

in the domain z1< z < z2. y(z) is an n-dimensional vector of dependent variables, A(z) is an nxn coefficient matrix and p(z) is an n-dimensional vector of nonhomogeneous (loading) terms. Any n/2 elements of y(z) are prescribed at the two ends, z = z1 and z2 as boundary conditions. It is clearly seen that mixed and/or nonhomogeneous boundary conditions are easily admitted during solution.

BVPs in ODEs, not only describe 1D elastostatic problems exactly but also 2D and 3D problems approximately whose behaviour is governed by a system of PDEs. The use of the well-known beam functions, Fourier series, harmonic analysis, etc. for dimensional reduction is a well-established procedure in mechanics, which helps in transforming PDE into ODE system.

It is sometime convenient to have a discrete dependent vector y(z) to be function of only one of the independent coordinate z while carrying out the finite element discretization of the prismatic domain defined by independent coordinates x and y. The basic approach to the numerical integration of the BVP defined by Eq. (1) is to transform the given BVP into a set of initial value problems (IVPs) – one particular (nonhomogeneous) and n/2 complimentary (homogeneous). The solution of the original BVP defined by Eq. (1) is obtained by forming a linear combination of one nonhomogeneous and n/2 homogeneous solutions so as to satisfy the boundary conditions at z = z2. This gives rise to a system of n/2 linear algebraic equations, the solution of which determines the unknown n/2 components of the vector of initial values y(z1). Then a final numerical integration of Eq. (1) with completely known initial vector of dependent variables y(z1) produces the desired results. It is intended here to extend the applicability of this procedure, which is documented by Kant and Ramesh [34].

Conceptualizing a finite element discretization in the lamina plane, a set of implicit first order ODEs is obtained. The solution vector of which consists of a set of fundamental dependent quantities whose number equals the order of the PDE system times the number of discrete finite element mesh nodes. Further, this fundamental set of quantities for any node consists of stress components and the corresponding displacements on the lamina plane. As noted earlier the availability of efficient, accurate and above all proven robust ODE numerical integrators for IVPs helps in obtaining the fundamental set of dependent quantities at all the nodal points through the thickness. Once the fundamental set is known, the auxiliary set of dependent quantities over the entire nodal set is computed simply by substitution of the values of the fundamental set of variables on the right hand side of algebraic expressions node-by-node. Initial experience with this novel formulation and the associated computational methodology is encouraging.

The proposed approach seems to have not got the attention that it deserves and we claim to be the first one to present a few non-trivial solutions. Some new results are available in recent publications [35-43]. The most significant advantage of this general methodology lies in the fact that both displacements and transverse stresses are evaluated simultaneously with same degree of accuracy through the numerical integration processes.

Functionally Graded and Piezoelectric Composites

Laminated composites are characterized by weakness at interfaces. A new class of materials named functionally graded material (FGM) has recently been proposed whose physical properties vary through the thickness in a continuous manner and are therefore free from interface weakness typical of laminated composites [44]. Piezoelectric materials transform elastic field into the electric field and the converse behaviour has led many researchers to study their controlling capabilities to structures [45]. Many recent studies have appeared on FGMs for plates and shells [46-61].

Conclusion

Various 2D simple theories for analysis of composites and sandwiches are discussed. Further, a novel partial discretization methodology is discussed in short. It is first of its kind of mixed model which is based on solution of two-point BVP governed by coupled first-order ODEs through thickness of laminates. Good agreement of the present results with the elasticity solution is observed. The most significant advantage of the present development lies in the fact that both displacements and transverse stresses are evaluated simultaneously at the finite element node with the same degree of accuracy through the numerical integration process and thus eliminating the post-processing module which is required in other analytical 1D, 2D and 3D displacement-based models for calculation of transverse stresses from in-plane stresses.

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