Indian Institute of Metals Series

Amol A. Gokhale
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Light Weighting for Defense, Aerospace, and Transportation

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Indian Institute of Metals Series

The study of metallurgy and materials science is vital for developing advanced materials for diverse applications. In the last decade, the progress in this field has been rapid and extensive, giving us a new array of materials, with a wide range of applications, and a variety of possibilities for processing and characterizing the materials. In order to make this growing volume of knowledge available, an initiative to publish a series of books in Metallurgy and Materials Science was taken during the Diamond Jubilee year of the Indian Institute of Metals (IIM) in the year 2006. Ten years later the series is now published in partnership with Springer.

This book series publishes different categories of publications: textbooks to satisfy the requirements of students and beginners in the field, monographs on select topics by experts in the field, professional books to cater to the needs of practicing engineers, and proceedings of select international conferences organized by IIM after mandatory peer review. The series publishes across all areas of materials sciences and metallurgy. An eminent panel of international and national experts acts as the advisory body in overseeing the selection of topics, important areas to be covered, and the selection of contributing authors.

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Light Weighting for Defense, Aerospace, and Transportation

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Series Editors' Preface

The Indian Institute of Metals Series is an institutional partnership series focusing on metallurgy and materials sciences.

About the Indian Institute of Metals

The Indian Institute of Metals (IIM) is a premier professional body (since 1947) representing an eminent and dynamic group of metallurgists and materials scientists from R&D institutions, academia, and industry mostly from India. It is a registered professional institute with the primary objective of promoting and advancing the study and practice of the science and technology of metals, alloys, and novel materials. The institute is actively engaged in promoting academia–research and institute–industry interactions.

Genesis and History of the Series

The study of metallurgy and materials science is vital for developing advanced materials for diverse applications. In the last decade, the progress in this field has been rapid and extensive, giving us a new array of materials, with a wide range of applications and a variety of possibilities for processing and characterizing the materials. In order to make this growing volume of knowledge available, an initiative to publish a series of books in metallurgy and materials science was taken during the Diamond Jubilee year of the Indian Institute of Metals (IIM) in the year 2006. IIM entered into a partnership with Universities Press, Hyderabad, and as part of the IIM book series, 11 books were published, and a number of these have been co-published by CRC Press, USA. The books were authored by eminent professionals in academia, industry, and R&D with outstanding background in their respective domains, thus generating unique resources of validated expertise of interest in metallurgy. The international character of the authors' and editors has enabled the books to command national and global readership. This book series includes different categories of publications: textbooks to satisfy the requirements of undergraduates and beginners in the field, monographs on select topics by experts in the field, and proceedings of select international conferences organized by IIM after mandatory peer review. An eminent panel of international and national experts constitutes the advisory body in overseeing the selection of topics, important areas to be covered, in the books and the selection of contributing authors.

Current Series Information

To increase the readership and to ensure wide dissemination among global readers, this new chapter of the series has been initiated with Springer. The goal is to continue publishing high-value content on metallurgy and materials science, focusing on current trends and applications. Readers interested in writing for the series may contact the undersigned series editor or the Springer publishing editor, Swati Meherishi.

About the Book

The current book "Light Weighting for Defence, Aerospace and Transportation" edited by Amol A Gokhale, N Eswara Prasad, and B Basu is part of the Indian Institute of Metals-Springer Nature Series on Metallurgy and Materials Engineering. It contains invaluable information on design, manufacturing, materials, and commercial aspects of light weighting in the form of nine articles written by world-known experts. The authorship represents a combination of academia, R&D, and industry. Among these articles, one is by Shri N Kiran Kumar, the then Chairman, Indian Space Research Organisation on light weighting at the system level, which demonstrates the importance of light weighting in India's most successful space programme. The uniqueness of the book lies in the fact that the data and the views presented in the articles are not readily available in papers that have been published in the past in scientific and technical journals.

The editors of the book are not only well versed and experienced with the subject, but are passionate about light weighting. They represent leading institutes, R&D organizations, and industries of the country, and have made immense contributions to the growth of the Indian Institute of Metals itself. I am sure that this book will elevate the high standards of the IIM-Springer Nature Book Series, synergizing the professional expertise of IIM toward effective knowledge dissemination. Going through the articles will be an enriching experience to the wider professional community across the world.

K. Bhanu Sankara Rao
Editor-in-Chief
Series in Metallurgy and Materials Engineering

Preface

While light weighting of structures is *desirable* in most engineering applications, it is *essential* in aerospace and automotive systems. The motivation for light weighting in aerospace systems lies in the possibilities of reduction in launch costs for rockets and missiles. The other advantage of light weighting is the ability to increase payload capacity of vehicles like aircraft and rockets. Reduced body armor weights can enhance endurance of soldiers and improve their effectiveness. For the automobile industries, light weighing is the key focus area with a long-term goal to improve fuel economy and also addresses the increasing demand for electric vehicles. Modern automobiles are able to offer a variety of electromechanical, intelligent, and safety systems without weight penalty, mainly because of reduced body and engine weight.

The papers contained in this volume were contributed to the 1-day Symposium on Light Weighting in Defence, Aerospace and Automotives, which was a part of the 55th National Metallurgical Day—71st Annual Technical Meeting composite event of the Indian Institute of Metals at BITS Pilani Goa Campus organized during November 13–17, 2019. The papers are equally divided between aerospace/defence and automotive applications. The authors are from India, the U.S., the Netherlands, and Germany and represent academia, R&D Establishments, and Industry.

What comes out of the collection of papers is that light weighting is an interdisciplinary activity involving multiple strategies. For example, it involves developing lighter materials, materials with improved properties, new design strategies, and even new manufacturing technologies. Hybrid materials and dissimilar materials joining allows reduction of overall structural weight without using any new materials, per se. Thus, the possibilities of light weighting are immense and ever evolving. This collection of articles gives a glimpse into the contemporary practices among researchers and industry and the principles behind them.

The editors are thankful to all the authors for contributing the articles and to the Publications Committee of the Indian Institute of Metals for supporting publication of this book in association with Springer Nature, Singapore/New Delhi. The team at Springers Publishers is ever supportive of such efforts and has provided many useful suggestions to make the book informative and interesting.

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About the Editors

Amol A. Gokhale is currently a Professor in the Department of Mechanical Engineering in IIT Bombay, where he teaches courses related to "Aerospace Materials" and pursuing research in shock and blast mitigation by foams and sandwich structures, processing and oxidation of niobium alloys, aluminium alloy thick products for airframes, etc. He did his B Tech from IIT Bombay in 1978, and M S and Ph D from University of Pittsburgh, USA in Metallurgical Engineering in 1980 and 1985, respectively. He served in DRDO for 30 years, retiring as Distinguished Scientist and Director, Defence Metallurgical Research Laboratory, Hyderabad in July 2015. At DMRL, he led research on aluminium lithium alloys for Light Combat Aircraft and INSAT series satellites, aluminium alloy components for torpedoes, crash resistant metallic foams, additive manufacturing, and very high temperature materials for hypersonic vehicles. He has been recipient of several awards from the University of Pittsburgh, DRDO, National Research and Development Corporation and the Indian Institute of Metals, and is a Fellow of the Indian National Academy of Engineering. He serves on national committees of NITI Aayog, the Ministry of Defence, Department of Science and Technology, IITs, Indian Institute of Metals, Indian National Academy of Engineering, etc. Since January 2017, he is the Convener, Technical Committee, Aeronautical Research and Development Board, DRDO. He is the Chairman of Research Council of National Metallurgical Laboratory Jamshedpur and Vice-President of Indian Institute of Metals.

N. Eswara Prasad B. Tech. and Ph.D. from IIT-BHU (Metallurgical Engineering Department) is currently serving as Outstanding Scientist and Director, Defense Materials and Stores Research and Development Establishment (DMSRDE), DRDO at Kanpur, India. He has made significant contributions to the design, development, characterization, and airworthiness certified production of materials for the Indian Space and Missile Programmes and aided Defence Materials Airwothy Production of several hundred Crores with >10 Type Approvals and 240 Certifications. He now specializes in several functional and special materials such as Stealth and Camouflage, SiC Fiber, Personal and Vehicle Armor based on

Modular Structures, and CNT-Based Materials and Components for Indian Defense. His prolific research resulted over 260 research articles in peer-reviewed national and international journals and conference proceedings, apart from 35 patents, 16 written/edited books, and 32 book chapters as well as 68 classified and unclassified, as also peer-reviewed technical reports and Editor of the only International monograph on Al-Li alloys and a widely referred 2-Volume Vade Mecum on Aerospace Materials and Material Technologies. He is the Chairman of NITI Aayog Committees on Personnel Protection Systems & Their Materials, DRDO Committee for National Materials Policy and Materials Standarisation Sub-Committee of MOD; Vice-President, SFA; Senate Member, IIT-Kanpur and IIT-BHU, Varanasi; AvH Research Fellow and MPI-Stuttgart Visiting Scientist; Fellow of IE(I), IIM, TAS, AeSI, APAM and InSIS; and recipient of 10 other National awards, including the prestigious GD Birla Gold Medal of IIM and National Aeronautical Prize of AeSI.

Biswajit Basu is Dy. Chief Technology Officer and Head of Aditya Birla Science & Technology Co. Pvt Ltd (ABSTCPL). He is the key architect in the foundation of the ABSTCPL as the R&D Hub of the Aditya Birla Group and led ABSTCPL as a unique multi-business R&D campus—one of its kind in India and inaugurated in 2012. He is also responsible for providing R&D strategic direction based on the identified centers of excellence to explore new avenues for growth. He has over 30 years of experience in R&D, digital engineering and innovation management, and joined the Aditya Birla Group in 2003. Prior to joining the AB Group, he was Senior Consultant in Tata Consultancy Services leading a R&D group on Engineering Simulation in the Tata Research Development & Design Centre which is the Corporate R&D centre. He was a Visiting Scientist at the Institute of Fluid Mechanics in Erlangen, Germany, from 1998 to 1999. He successfully led and partnered numerous technology and product development programs for a range of industries in Metals and Chemical sectors. He completed his bachelor's degree in mechanical engineering from Jadavpur University, Kolkata and master's degree in mechanical engineering from the Indian Institute of Science, Bangalore. He completed PhD in Fluid Mechanics and Materials Processing from the Indian Institute of Technology, Bombay in 1991. He was the President of Indian Institute of Metals during 2017-18. He has over 30 Journal Publications, 45 Conference presentations, and few patents. He is recipient of Young Metallurgist Award from Indian Institute of Metals and Young Associate Award from Indian Academy of Sciences. He has been key note speaker at several National and International Conferences.

Chapter 1
Opportunities for Lighter Weight and Lower Total Cost Component Manufacturing

Jim Williams, Brian Post, Lonnie J. Love and Craig Blue

Abstract This paper describes how a relatively new manufacturing technology known as additive manufacturing (AM) can enable creation of more mass efficient components when compared to those created by conventional or subtractive manufacturing (SM). An important element in the use of AM is re-thinking the design approach when completely new shape possibilities are enabled. Similarly, creative use of AM also can enable significant part count reduction. In order to make the case for the potential of AM, the more common AM processes are described and illustrated. As with any new technology, there come challenges during the reduction to practice phase of AM. Some of these challenges have been addressed and solved. Others are a work in progress and the approach to possible solutions to some of these is described.

1.1 Introduction

The design intent of a component is to fulfill as efficiently as possible the requirements imposed by the system that incorporates the component. For structural (load bearing) components, which are the only class of components we will consider in this paper, the primary requirement is to carry the externally imposed loads without instantly failing. However, over time, the sophistication of high value manufactured systems has increased. Consequently, additional secondary requirements have been added and these affect the design approach. Among these additional requirements can be: weight, useful life (particularly if cyclic loading or elevated temperature operation is involved), cost, production volume and manufacturability. Today, essentially all high value components are manufactured using the traditional methods of machining the

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final shape from a forging, a casting or from bulk wrought product (sheet, plate, bar or billet). This method is often called "Subtractive Manufacturing" (SM) because this quite accurately depicts the manufacturing process, i.e. start with a larger work piece and selectively remove stock to obtain the desired shape that meets the geometric shape defined by the component design.

In recent years, a completely different type of manufacturing process has been developed by which the component is created by selectively and incrementally depositing material where it is needed to obtain the desired shape defined by the component design. Collectively this process is called Additive Manufacturing (AM) or, as is more commonly found in the popular press, 3D Printing. There are several distinct AM processes as defined, at least, by input material and the heat source used to fuse the input material as the component is being produced. In this paper AM and 3D Printing will be treated as synonyms.

In principle, the shape making capability of AM opens the possibility of completely new designs with totally different geometries that meet design intent. AM also introduces the possibility of creating components that have the same fit and function as earlier components but which are assembled from several smaller components made by SM. The attendant reduction in part count can significantly impact overall cost provided the cost model accounts for assembly cost and inventory, system reliability and other logistic requirements imposed by the use of the smaller components produced by SM.

History shows that acceptance of revolutionary new manufacturing processes such as AM have been slow in part because of lack of familiarity of working design engineers and because of the perceived risk associated with a process that is so different. The result of this slowness is the persistence of incremental designs in subsequent generations of components, often at the expense of weight and cost. A real example of this is the reluctance to consider the use of super plastic forming and diffusion bonding to replace subsystems made from Ti alloy sheet that have been fabricated from many smaller components.

In this paper, we will describe the AM processes in a general way and discuss how the use of this new manufacturing process can impact design in a way that enables weight reduction and cost reduction simultaneously. Clearly, there is much to do to reduce AM to practice and some of these tasks will be described as "challenges" that need to be addressed to broaden the appeal of AM to the traditional design and manufacturing community.

1.2 Brief History and Description of Additive Manufacturing

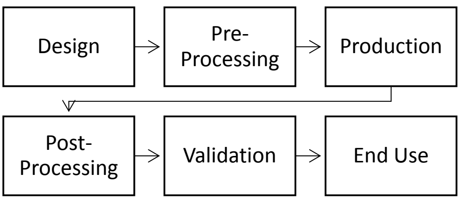
Additive manufacturing (AM) now is the official industry term (cf. ASTM Standard F2792) for all applications of the process of joining materials to make objects from 3D data. This terminology has been developed to contrast with traditional "subtractive" manufacturing (SM) processes where material is removed by cutting, grinding, or other methods to form the final component. AM processes usually consist of the deposition of layers of material in sequential order to form the final component. 3D printing, coined by MIT, was the term previously attributed to these processes and is widely adopted as the common name by the popular press. 3D printing is used interchangeably with additive manufacturing by industry professionals. Rapid prototyping has also been used, especially in the 1990s. The adoption of the AM terminology represents the maturation of the technology from prototyping, for form and fit, to end use component production. To avoid confusion, we will use AM in this paper, but it should be considered a synonym for 3D Printing.

Research in additive manufacturing (AM) began in the late 1960s and culminated in the first commercialization of stereo lithography in 1987 from 3D Systems (Wohlers and Gornett 2014). Thus, although AM is not a novel concept, recent developments in AM technology have increased production rates and reduced costs, enabling increased adoption of AM and greatly increased component complexities (Smartech Marketing Publishing 2014). From 2012 to 2014, the AM industry grew at a rate of 33.8% per year (Wohlers 2015), a pace that has been sustained through 2015. Some of the earliest adopters of AM were in the automotive industry (Smartech Marketing Publishing 2014), where rapid prototyping using sterolithography to produce a plastic prototype to verify component form and fit dramatically reduced development time and cost. Today, the availability of 3D computer graphic software has largely eliminated the need for this interim step and components made of the intended structural material are produced directly using AM methods.

Moreover, the unique attributes of AM enable increased component complexity and the ability to reduce part count though the use of design synthesis to produce "clean-sheet" designs that benefit from the unique AM attributes and, therefore, can integrate several individual components into a single one. However, despite these possibilities and the recent improvements in AM production rates and costs, AM has yet to directly replace the conventional processes manufacturing, e.g. casting and forging, used in industries that are based on economies of scale. Irrespective of the specific production process the general process flow for component design is schematically shown Fig. 1.1.

Each step of the process is driven by the end use requirement case. Desired form, fit, and function drive the design, the process and material selections, the processing parameters, the finishing processes, and the validation steps required to certify the component for use in the intended application. While the production

Fig. 1.1 AM process flow



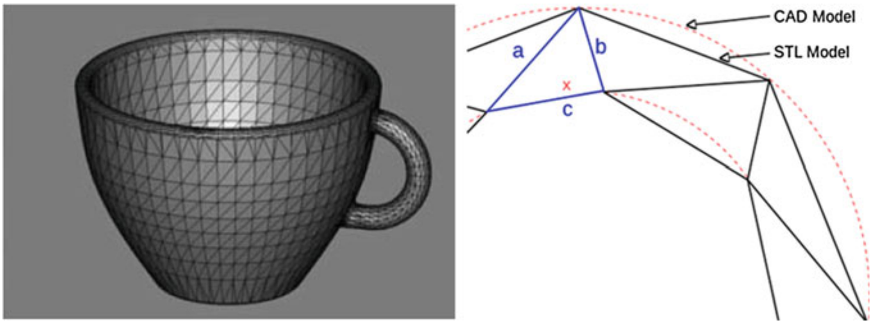


Fig. 1.2 STL file faceted approximation of CAD geometry (*Source* Oak Ridge National Lab.)

process is automated, variation introduced from operator interactions during the pre-processing and post-processing operations have significant impacts on the final component characteristics. The acceptable amount of variability depends on how critical the performance expectations of the component are.

While the individual processes vary significantly in their materials and processing methodology, the framework and software is universal. The industry accepted file format for AM is the STL, short for Stereolithography which was developed in the early 1980s. This format represents a computer aided drafting (CAD) model's geometry by faceted surfaces as shown in Fig. 1.2.

This geometric model is virtually "sliced" into layers and used to generate deposition paths for each layer of the component. Each layer is deposited sequentially on top of the previous layers to form the finished component. The production process flow is shown pictorially in Fig. 1.3.

Support material is removed from locations with overhangs and finishing operations are performed to meet the specifications on geometry, surface quality and/or resolution. Often these finishing operations involve sanding, vapor distillation smoothing, or machining. The benefits realized through AM are achieved through elimination of tools such as forging dies, reduction in production waste, creating functional structures, and in the production of components where traditional manufacturing operations are either prohibitively expensive, require significant tooling for limited production runs or not possible by traditional processes at all. The elimination of production tooling also substantially reduces production time since no waiting for tooling is required. Also, as will be discussed later, there are cases where AM enables creation of shapes that cannot be made by subtractive or any other manufacturing process.

The evolutionary rate of AM technologies is accelerating as new developments and advances in AM are occurring daily. Thus, the present review is a guide illustrating a portion of the options that AM enables. The findings, detailed in later sections, also illustrate areas in which research efforts could be directed toward maturing and accelerating the adoption of AM where practical. In the near term, AM processes

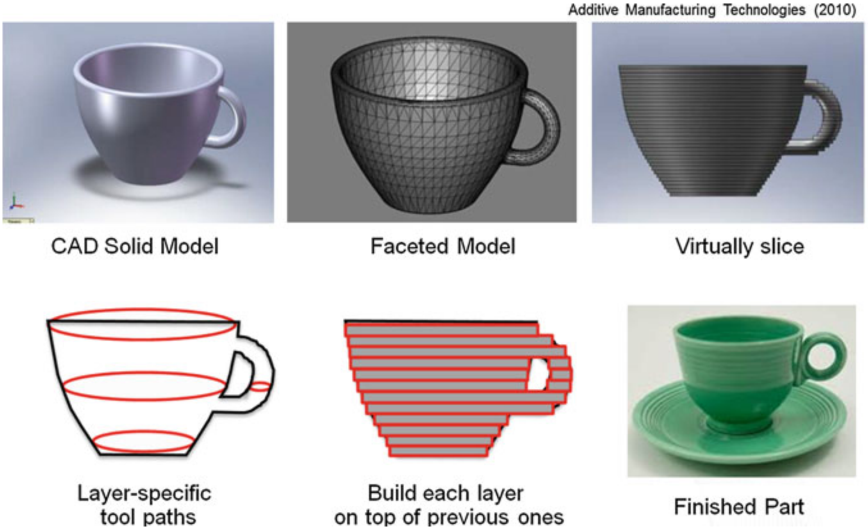


Fig. 1.3 AM production flow (*Source* Oak Ridge National Lab.)

need further research and refinement before implementation at large scale in new-component production. However, technology and process improvements are occurring rapidly, steadily reducing projected development times of higher-performance components and systems that AM processes cannot produce. Costs of AM continue to decline, illustrating that there is potential for wider-scale deployment of in use parts. The following section covers a review on current metal AM technologies. Since the focus of this manuscript is metallic structural components, we will not cover polymer AM systems even though there has been tremendous progress in this AM domain. While emerging R&D activities, specifically printed composites, will enable future production of end use parts, we will not cover those technologies in this paper.

1.3 Overview of AM Processes for Metal-Based Manufacturing

There are two basic groups of AM processes as determined by the feedstock used as input material. These materials are powder and solid material, either wire or thin foil. Within each of these there are a number of variants. We will attempt to summarize these in a manner that allows comparisons of the product of the process but many details will not be included here.

For the powder based processes, which are arguably most common today, there are basically two variants: powder bed and direct energy deposition, one of which is often called "blown powder". Among these there are numerous deposition machines that are commercially available today. Within the powder bed process domain, there are three process subsets as defined by the source used to fuse the feedstock during component creation. These sources are binder jet, electron beam or a laser. The blown powder process only uses a laser heat source. Today, the blown powder process is less commonly used but has an important role in the overall maturation of AM. Because it is not a major factor in actual component creation, it will not be further discussed in detail here. Among the wire fed processes in use today, there are two possible heat sources: electron beam and transferred plasma arc.

These two basic AM processes (powder based and solid material (wire or foil) based) each have advantages and weaknesses. In fact, the two can be viewed as complementary. Within the powder based processes there are currently three standard processes for AM fabrication of metallic components: powdered bed fusion, directed energy deposition and binder jet. For these powder based processes, the powders are on the order of 50–200 μm in diameter with all but binder jet being limited to 40–60 μm. The final builds achieve a surface finish roughness and geometric resolution that mimics the powder diameter (Spierings et al. 2011; Gong and Anderson 2012; Butscher et al. 2011). The powders are fabricated into final components either by using precise, accurate direction of intense thermal energy (directed energy deposition and powdered bed fusion) or by using a binding agent (binder jet) to bond powder particles together locally to form a solid. The thermal energy-based approaches physically melt the powder during the build, with little to no secondary processing. The binder jet process consolidates the powder with a low-melting-point polymeric binder which is then cured to form a green shape. Secondary post-processing removes the binder and either back infiltrates with a lower melting point metal through capillary attraction or directly sinters the powder to consolidate it. The following sections and subsections detail some of the specific attributes and uses of the different AM processes for metals. The solid material fed processes use wire or thin foil as feedstock.

1.3.1 Powder Based Processes

The following are brief descriptions of the three powder bed processes currently in use today. These are described in the order of the extent of current use or according to the level of development activity being devoted to maturation of these processes, either in machine development or process refinement.

1.3.1.1 Powder Bed Fusion

Although the binder-jet process produces sand cores and could be the most scalable process for metals, the most common and mature metal AM process for end use components is powder bed fusion. Rather than use a binder to attach and later sinter metal powders, powder bed fusion uses an intense energy source, such as a laser or electron beam (e-beam), to sinter or melt the powder. For laser based powder bed systems, a gimbaled mirror directs the energy from the source to the powder. The advantages of this process are that it transforms the powder by selectively fusing it directly into the final component; this process is distinguished by the high degree of spatial resolution and the high-quality surface finish compared to other AM processes. The unmelted powder bed remains at a relatively cool temperature making removal of this powder easy. This is critical for powder removal on internal fluid passages (fuel injectors, hydraulic components…). However, the process is relatively slow compared with conventional techniques such as casting and can result in component builds that experience very high internal residual stress (Gibson et al. 2015; Brice and Hofmeister 2013; Daymond and Johnson 2001; Wu et al. 2014). Residual stress issues associated with the process initiate and can localize at the base of the build, as the process initiates the first production layers on top of a build plate. After the component is built, it is heat treated to relieve the stress and then the build plate is cut off.

The electron beam (e-beam) melt technology is a more recent alternative for powder bed fusion (Gibson et al. 2015). Rather than using a laser and gimbaled mirror, e-beam technology uses electromagnetic fields to guide a stream of electrons to selectively melt the powder in the desired location (Gibson et al. 2015). The advantage of this process is that it is possible to defocus the beam and rapidly preheat the powder bed close to the melting temperature. The e-beam is moved rapidly so that numerous weld pools are generated nearly simultaneously. This distribution of thermal input improves local thermal distribution, increasing the deposition rate and significantly reducing residual stress so that there is little need to weld the component to the start plate. The disadvantage of the e-beam process is that the unmelted powder is lightly sintered together, which affects the surface finish and makes component and powder removal more labor-intensive than in laser powder bed fusion (Gibson et al. 2015). Furthermore, the powder bed must be allowed to cool (possibly for longer than a day) before it can be removed from the machine and post processed reducing the productivity of the expensive deposition system.

Both approaches to powder-based AM result in a greater degree of densification of the finished build, compared with the binder jet process. This reduces secondary processing requirements such as hot isostatic processing (HIP), with commensurate reduced overall process time and costs. Although there are advantages to both e-beam and laser-based powder bed processes, they require either high-vacuum or inert gas environments inside the build chamber, which makes scalability a challenge and adds to production throughput cost. Both laser and e-beam processes lose resolution working in distal regions of the build volume which also limits component size and accuracy. Recent patent expirations (Ford 2014) have opened opportunities for new businesses to enter the AM technology space, which will increase competition between suppliers and potentially lead to further gains in the finish quality of AM products.

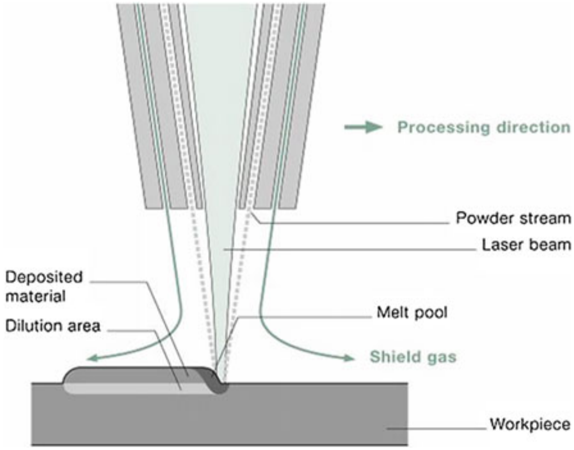


Fig. 1.4 Schematic of direct energy deposition process (This process is highlighted in the section. Image taken from LPW Technology, Candel-Ruiz et al. 2015)

1.3.1.2 Direct Energy Deposition

Directed energy deposition is one of the earliest metal AM processes and is based on feeding a metal powder into the path of a laser, creating a melt pool. As illustrated by Fig. 1.4, directed energy deposition moves the powder feed and laser beam together, selectively adding molten material layer by layer. The advantage of the process is that it can grow components out of a plane, eliminating the need for a layered process, while a shielding gas protects the melt pool from oxidation during solidification (Gibson et al. 2015). Furthermore, the process enables multiple simultaneous and individual material feeds, enabling in situ deposit composition modification by blending different materials. The primary application for this technology is repairs and surface coatings. The specific capability to engineer material composition and property gradients locally within the build process holds extraordinary potential. The disadvantages of the process are the low deposition rate, poor surface finish, and lack of support material necessary for detailed component complexity. Since the inception of this process, the technology has matured and is currently classified under several different names: most commonly Laser Engineered Net Shaping (LENS), but also laser powder forming, laser metal deposition, direct metal deposition, direct laser deposition, laser cladding, laser deposition welding, blown powder and powder fusion welding.

1.3.1.3 Binder Jet Printing

The AM process that currently seems to be the most adaptable to large-scale production is binder jet printing, as illustrated by the availability of production line-scale printers, which are capable of creating build volumes containing a single or multiple components nearing 2 m^3 in total volume at build rates nearing ½ m^3/h. (Stevenson et al. 2013). Binder jet printing is a powder bed process that uses an inkjet head to deposit a binder (e.g., polyethylene glycol) to build objects from powdered media. The binder is quickly photo catalytically cured, and the process repeats, building the component layer by layer. For components with internal passages, uncured powder in each layer serves as the support for successive layers. When the build is complete, the component is in a fragile "green" state and must be carefully removed from the powder bed. A secondary oven curing process is then used to partially sinter the component and to remove the binder. Although this process is well suited for large-scale production, the binder removal results in relatively high component porosity (greater than 30%) (Butscher et al. 2011; MCE-5 2009). To increase final component density, a lower-melt-temperature material (e.g., bronze) can be used to back-infiltrate the component during the sintering process. The result is that a fully dense component is produced using composite materials (Gibson et al. 2015).

The advantages of this process are the low residual stress during the manufacturing process; the capability to easily fuse high-temperature materials, the ability to use larger input powder sizes and the ease of scaling it to larger-volume printing, as no vacuum or inert deposition chamber is needed for this AM process. The primary disadvantages are the fragile condition of the green component before sintering and the need for multiple steps (MCE-5 2009; Brice and Hofmeister 2013; Daymond and Johnson 2001), which ultimately add to the cost of final printed components. This process is well suited to metals, and it was originally developed for printing complex sand casting molds. Currently, sand molds created using binder jet printing are used by original equipment manufacturers like Ford Motor Company (Smartech Marketing Publishing 2014) in the automotive industry to develop prototype engines, and by startup companies with novel technologies, like MCE-5, which used the technique to develop its variable-compression engine (Stevenson et al. 2013; MCE-5 2009). Binder jet printing of sand cores reduces production time to hours and is very adaptable to design changes without retooling costs (Stevenson et al. 2013). It has an inherent potential to contribute to increased vehicle fuel economy, as it can reduce design integration times by approximately 6 months, enabling further refinement and optimization during the same development time period (Stevenson et al. 2013).

1.3.2 Solid Material Fed Processes

There are two AM processes that use different forms of solid input material: wire and foil. These are quite different but only the wire fed processes will be described in detail for reasons briefly mentioned later.

1.3.2.1 Wire Fed Processes

There are currently three AM processes that use wire as the input material under development. These have some commonalities and differences; notably the heat source, the actual deposition mechanism and the deposition environment. All three processes are capable of significantly greater deposition rates than the powder bed or direct powder fusion processes. Each process also use a substrate typically consisting of a plate of the same alloy as the deposit. The processes typically have less precise shape definition capability than the powder bed processes but, for relatively heavy components, the higher deposition rates more than offset the post process machining requirement.

One of the wire fed processes uses an electron beam (e-beam) heat source operating in a vacuum and moves the wire feeder and electron beam to the desired point of deposition. This process has been demonstrated to be capable of making near net shapes that weigh less than or equal to twice the final desired shape. The ratio of initial starting weight to final machined weight in AM and SM is generally known as buy:fly (BTF). As a reference, complex shaped airframe components machined from forgings or plate material can have a BTF of as much as 20:1. Because the process is performed in a vacuum, there are or can be component size limitations imposed by the available chamber size. Also, for the more commonly used Ti alloys, which typically contain 6–8 wt.% Al, evaporation of Al during deposition in the vacuum must be compensated for by increasing the Al concentration of the wire feedstock.

The other wire fed process uses a fixed transferred plasma arc torch as the heat source and manipulates the deposition “target” under the molten metal “plume” with a robot. This process is performed in an inert gas (typically purified Ar) filled dry box operated at slight positive gas pressure to prevent oxygen and nitrogen back streaming. This process also has much higher deposition rates and has been shown to be capable of producing components that have BTF of 2:1. Clearly, the exact BTF value for both the wire fed processes depends on the geometric complexity of the particular component. Presumably the capacity of the robot to manipulate very heavy components can pose a challenge but this is a minor concern given the typical size of component that is of current interest.

Recent efforts have focused on utilization of a laser, rather than an e-beam, for wire fed processes. The advantage of the laser is finer control of the energy source (power from the laser) as well as using an inert cover gas rather than a vacuum.

1.3.2.2 Sheet Lamination

A second methodology to manufacture complex metallic components from solid material is sheet lamination. Rather than using a powder or wire as the feedstock. Sheet lamination uses ultrasonic energy to fuse layers of several micron thick foil together to rapidly grow near net shape components. The advantage of the process is the speed (fusing full layers rather than building a single layer voxel by voxel). However the process uses thin foil for input material which, in high strength engineering alloys, is very expensive to produce. It also requires post process in situ machining resulting in wasted material. Neither of these disadvantages are insurmountable, but make this process less attractive from a cost standpoint. Consequently, this process will not be illustrated or discussed further here.

1.4 Opportunities for Producing High Value Components by AM

1.4.1 System Design Based on AM

As described earlier, the primary benefits of AM include optimization of component design for weight reduction, part count consolidation (reducing the number of parts in an assembly through novel design enabled by AM), and cost reduction through tool-less manufacturing for low-volume production. The impact of the tool-less aspect of AM on cost has often been underestimated because the time required to create a tool such as a forging die or a wax die for investment casting add significantly, but indirectly, to cost but is seldom tracked and therefore is not included.

AM offers possibilities for accelerating weight reductions through novel and complex geometries such as lattice structures that have been created using both laser and e-beam manufacturing. These structures have been demonstrated to offer improved strength per unit of mass (Cansizoglu et al. 2008). One of the best examples of the impact of AM is the GE fuel nozzle (see Fig. 1.5). The design reduced an assembly from 20 individual parts in the assembly to one single manufactured part. Furthermore, the AM part is 25% lighter and 5X more durable than the original assembly.

Furthermore, as shown in Figs. 1.6 and 1.7, AM enables the integration of complex internal structures (such as fluid passages) that are not constrained by traditional limitations of conventional SM (e.g. round holes and straight fluid passages). The basic design intent (integration of hydraulics within a lightweight AM structure)

Fig. 1.5 GE AM fuel nozzle (Photo and information courtesy of GE Additive)

Fig. 1.6 Functional ORNL AM hydraulic hand (*Source* Oak Ridge National Lab.)

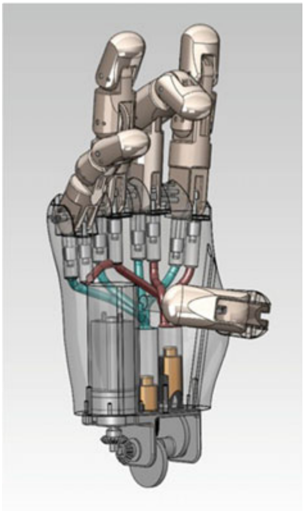


Fig. 1.7 Transparent view of hand design Robotic showing red and blue tubular fluid passages (*Source* Oak Ridge National Lab.)

of the AM hand was scaled up to the production of a full-scale set of underwater hydraulic arms for the Navy (see Figs. 1.8 and 1.9). As a point for comparison, the original set of arms were manufactured through conventional SM processes. Each arm had approximately 230 manufactured parts, took 3 months to design, 3 months to develop the manufacturing drawings and 3 months to manufacture. Each AM arm in Fig. 1.8 has 35 AM parts, took 3 months to design, 1 week for the design package and 1 week to manufacture. The surface finish required minimal post processing (honing

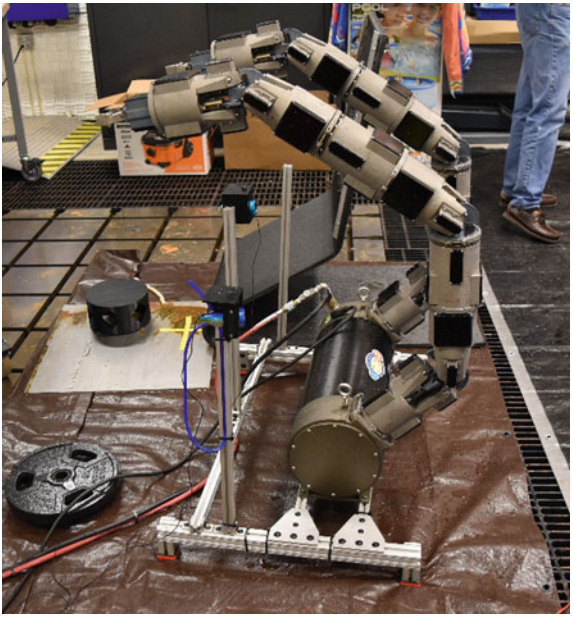


Fig. 1.8 Dual hydraulic AM arms (*Source* Oak Ridge National Lab.)

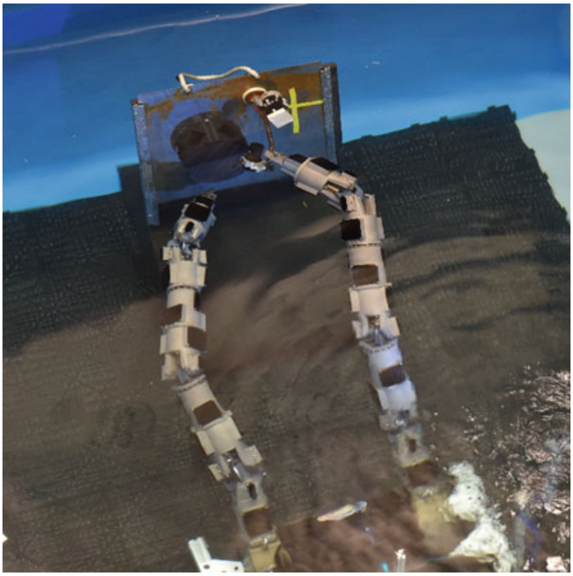


Fig. 1.9 Dual arms in operation (*Source* Oak Ridge National Lab.)

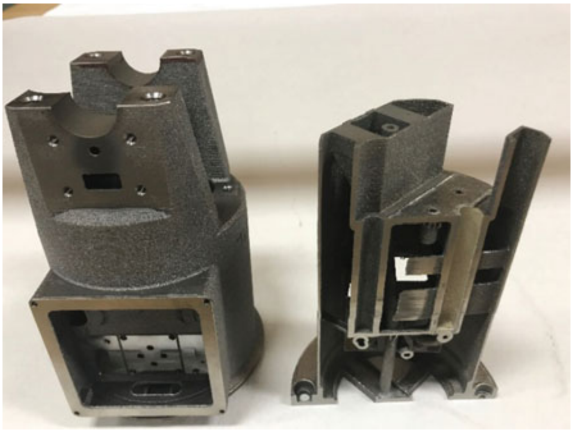


Fig. 1.10 Section view of AM component (*Source* Oak Ridge National Lab.)

piston bores and finishing o-ring glands and face seals). Furthermore, the original arms weighed approximately 35 lbs whereas the AM arms weighed 20 lbs. The system is designed to have no hoses (all hydraulics are integrated into the structure as shown in Fig. 1.10) with open internal cavities for routing wiring harnesses. The arms have no external penetrations and are designed to be neutrally buoyant and, due to the simplicity of the design enabled by AM, can be disassembled or assembled in under an hour.

1.4.2 Weight Reduction Through Lattice Structures

As another example, a simulation assessment of lattice structures for use in engine components was conducted by the University of Bath. The results illustrated the potential for integrating a lattice into the center section of a piston, as shown in Fig. 1.11. The simulation prediction results suggest it may be possible to reduce piston mass by 9% (Angel et al. 2015) with little to no change in structural integrity. This also would allow reducing the connecting rod and crankshaft mass due to lower operating loads imposed by the pistons. Such system impacts need to be included in revised cost models.

1.4.3 Functional Assemblies

Recently, an AM optimization and opportunity study of a Delphi-based diesel fuel pump design was conducted by the AM consultant Econolyst (now the Strategic

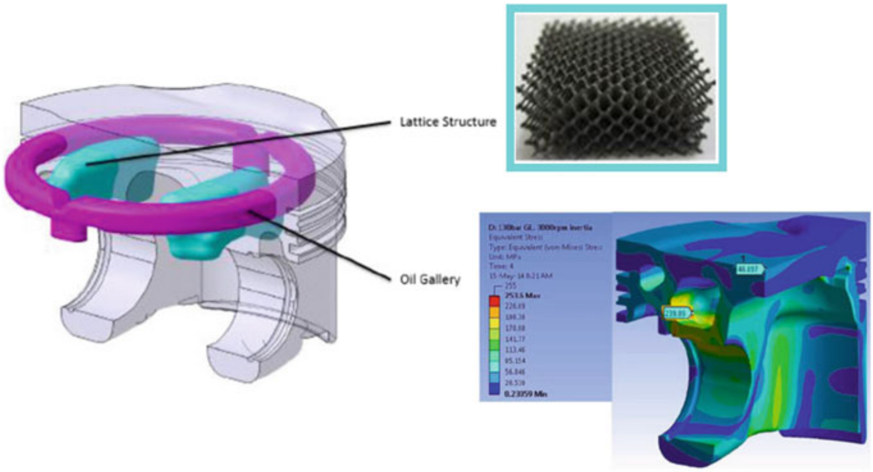


Fig. 1.11 AM possibility for reducing piston weight through lattice integration (Figure adapted from Reyes, Belmonte et al. (Angel et al. 2015))

Consulting Team at Stratasys) in association with Loughborough University (Benatmane 2010). The component investigated was a production component for a European midsize sedan diesel with a component lifetime of 300,000 km (186,000 mi.). In Delphi's conventional cast product, several post-casting, computer-numerically-controlled machining operations are needed for drilling holes and ensuring component tolerance accuracy. These add cost, time, and logistic complexity to the production. Additionally, Delphi needed further subsequent processes to ensure leak prevention. Using the clean-sheet Design For AM (DFAM) approach; a majority of the secondary machining operations were eliminated. Furthermore, the fluid flow paths were re-engineered using a topology optimization routine that could improve the pump efficiency, reduce internal flow losses and restrictions, and reduce overall losses. This approach is similar in concept to work by Cooper et al. (2012) for an F1 racecar hydraulic transmission shifting valve. Their results show that DFAM enabled clean-sheet design with flow time reductions ranging from 100 to 250% compared with the conventional manufacturing approach. The design and geometric freedom possible with AM enables these (and other) geometric-based opportunities in clean-sheet AM specific builds.

In the Delphi study, two materials; the powder form of the cast aluminum alloy A380.0 used in the original component and a stainless steel (316L); are studied using a selective laser melting process. The study not only analyzes the energy associated with manufacturing the conventional and AM components, but also quantifies the in-use and post-use energy, encompassing a cradle-to-grave–based analysis. The resulting AM and conventional manufacturing designs are presented in Fig. 1.10.

Although the designs of the AM and the CM components in Fig. 1.12 are visually very different, there is no geometric difference in fluid path connection or pump drive locations between the two components. Besides the opportunity for improved flow

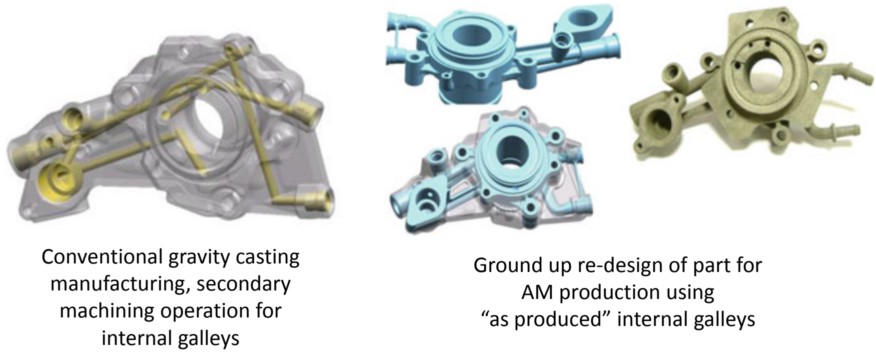


Fig. 1.12 Fuel pump used in Delphi Econolyst case study (Images are taken from Reeves 2013)

path and reduced secondary machining operations, the AM component also had considerable weight savings compared with the conventional component, even if made from ~2X denser 316 SS. These weight savings not only translate to in-use benefits but also are realized at the raw material acquisition, transport and production stages, as less material is required overall. The opportunity for reduced component complexity could enable cost savings and a motivation for the manufacturer to implement this process if the existing cost models are revised to fully account for the impact of AM. This especially true when it is combined with vehicle weight reduction and manufacturing-energy-intensity savings. Such global cost models typically need development or refinement when the use of revolutionary manufacturing technology such as AM is included.

The Delphi study estimates that for the denser 316 SS component, approximately 1 kg in weight savings could be realized in the total material weight (i.e., final component and production material) with the AM component. Likewise, if the AM component were made from 380 Al (like the CM component), the total material weight savings could be nearly 2 kg for the AM component compared with the conventional gravity die cast component. Using these weight savings, the study estimates vehicle fuel savings resulting from the component-level weight savings by calculating the vehicle's energy use over its 300,000 km (186,000 mi) lifetime. These results show that the potential energy savings of AM is significant, especially in the total energy and in-use portions. Moreover, the energy and CO_2 savings during use in service can be very significant, ~ 4–5× reductions, respectively. The findings highlight that a large part of a component's overall life cycle energy consumption is during the in-use phase. Note that the in-use energy savings calculated in this analysis are simply a function of the weight savings of the AM approach and are not based on any added functionality or component performance resulting from the redesign (it is assumed to be equal in performance and engine friction). Thus, there is the potential for additional energy benefits from improvements in component efficiency that could be realized by AM, as discussed earlier. The total energy and in-use portions of the findings are presented graphically in Fig. 1.13.

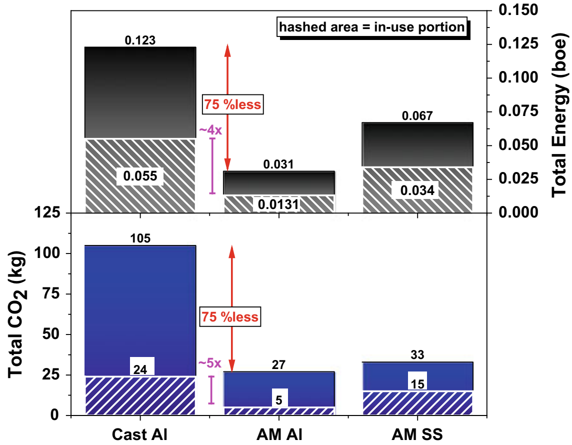


Fig. 1.13 Life cycle analysis of Delphi diesel pump housing (Produced using data from Benatmane 2010)

1.4.4 Increase Performance Through AM Design

In 2014, ORNL's Power Electronics and Electric Machines Group showcased a 30 kW power inverter that had 3 times the power density of a commercially available unit. The ORNL inverter design used wide bandgap electrical components and a redesigned (through AM) inverter heat sink that could serve three functions: heat sink, structural member, and conductive bus bar. The redesigned AM component enabled lower electrical losses by placing temperature-sensitive components closer to previously high-temperature areas, as seen in Fig. 1.14 (Ozpineci 2015; Millikin 2014). In addition, the heat sink design enabled the team to reengineer the capacitors

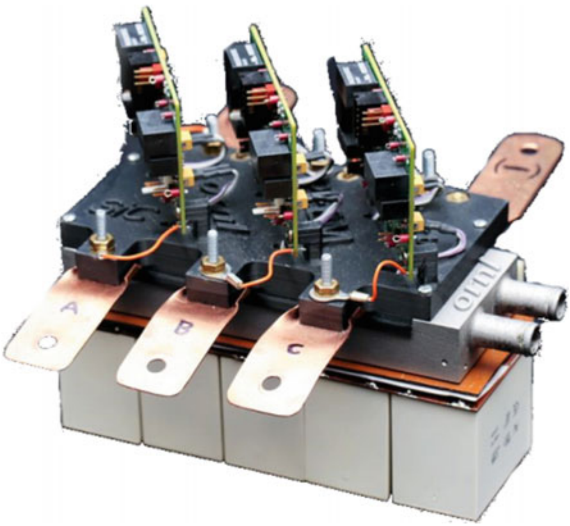


Fig. 1.14 ORNL power inverter (Inverter 1) incorporating AM components for better packaging to improve power density (Millikin 2014)

Table 1.1 Prototype AM-produced inverters developed by power electronics researchers at ORNL (Data compiled from Millikin 2014, Vehicle Technologies Office 2015)

Inverter	Cooling	Power level (kW)	WBG	Power density (kW/L)	Specific power (kW/kg)	Efficiency (%)
1	Liquid	10	SiC	13.3	11.3	99
2	Air	10	SiC	2.26		98
2020[a]	Neutral	55	SiC	13.4	14.1	~97[b]

[a]Target inverter derived from figures in EV Everywhere Challenge Report and Electric Drive annual reports (Millikin 2014, Vehicle Technologies Office 2015)
[b]97% is an average estimation of the efficiency needed by the inverter to meet the DOE 2020 target of 94% system efficiency (by taking the square root). System efficiency is a multiple of the inverter efficiency and motor efficiency

used in the inverter by moving to a parallel array of smaller capacitors rather than fewer large "brick type" capacitors, thereby further reducing the heat output (e.g., improving system efficiency). Using 50% AM parts, the group was able to achieve nearly 98% (Vehicle Technologies Office 2015) system efficiency, with power density and specific power near 2020 DOE targets, as illustrated in Table 1.1.

The team found that, in use, the inverter's operating temperature range was between 100 and 200 °C. Although this operating temperature range was acceptable, there exists an even greater opportunity to improve performance. Specifically, Table 1.1 illustrates that in the operating temperature range, the aluminum materials used in the heat sink for the prototype inverter design are less thermally conductive than conventional manufacturing materials, introducing inefficiency into the AM-produced inverter. Based on the data in Table 1.1, by developing an aluminum alloy for the direct metal laser sintering (DMLS) process that can achieve higher thermal conductivities matching those of the CM Al 6061 alloy, there is further opportunity for AM to increase the inverter's efficiency and reduce its size.

1.5 Emerging Trends in AM

As advancements in AM processes and controls emerge, scientists and engineers are learning that AM may enable the production of components and systems previously not possible.

1.5.1 Tailored Materials/Microstructure Control

There are measurable benefits that in-build property control can enable. Dehoff et al. (2015) showed at ORNL's Manufacturing Demonstration Facility (MDF) that in an otherwise basic AM block (see Fig. 1.15), preferential grain orientation during an AM build could be precisely managed through careful control of process parameters. Although it is not visible with the naked eye, neutron imaging of the block revealed that the material grains were specifically and purposefully oriented during the build to spell "DOE" within the block. The neutron image is illustrated in Fig. 1.15, which provides further confirmation of the grain structure through electron backscatter diffraction along different lattice directions in Fig. 1.16.

The use of AM to affect grain growth is not unique to Dehoff et al. (2015). Previous efforts in e-beam and laser melting AM demonstrated the ability of varying process parameters to affect controlled grain growth in components. Studies (Zhou et al. 2015; Li and Gu 2014; Dinda et al. 2009) show that changing process parameters such as scan length, focus, and current can change the thermal gradient and

Fig. 1.15 **a** Photograph and **b** energy-selective neutron radiograph of a 5 mm thick slice of the 1 in thick Inconel 718 sample (Image from Dehoff et al. 2015)

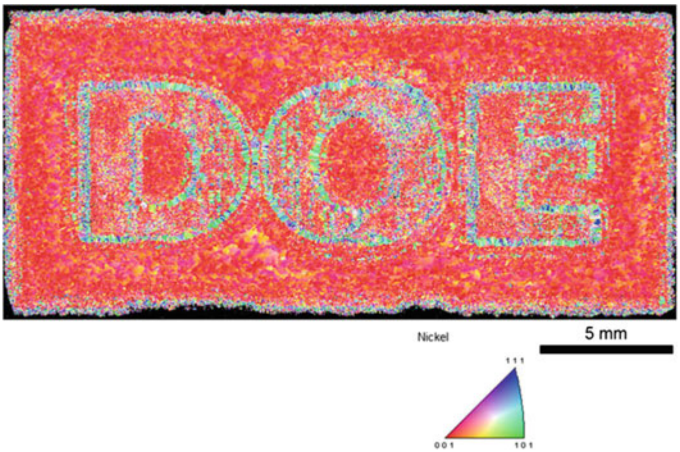


Fig. 1.16 Orientation image map obtained from electron backscatter diffraction confirming grain orientation control through a deliberately controlled e-beam process (Data compiled from Millikin 2014, Vehicle Technologies Office 2015)

solidification interface velocity. However, these findings were more oriented toward characterization of the process parameters, whereas the high-fidelity control presented in Dehoff et al. (2015) is the first known public display of microstructure control *during* a deposition process that could locally control the preferred orientation while maintaining a different orientation for the bulk surface. Dehoff et al. (2015) work found that scanning speed was an important parameter. The scanning velocity enabled direct changes in the melt pool during the component build from an ellipsoidal shape similar to fusion welding (~0.5 m/s) to a linear melt pool (>3.5 m/s). The results were large variations in gradient and solidification interface velocity that could be exploited for microstructure control, where results are presented in Table 1.2.

Solidification maps like the one in Fig. 1.17 have been developed from analytical models for fusion welding, which serve as good approximate representations of the physical and thermal processes taking place during e-beam and laser AM.

Once the relationships between AM process parameters for gradient and solidification interface velocity are understood, using AM to control the material properties is possible. The results of Dehoff et al. visually illustrate the power of AM, but

Table 1.2 Scan strategies by region of component (Data compiled from Millikin 2014, Vehicle Technologies Office 2015)

Scan strategy	Region	Grain growth
1	Boundary of letters	Highly misoriented, equiaxed
2	Bulk	<001> columnar
3	Interior of letters	Mixed mode, a combination of columnar and equiaxed

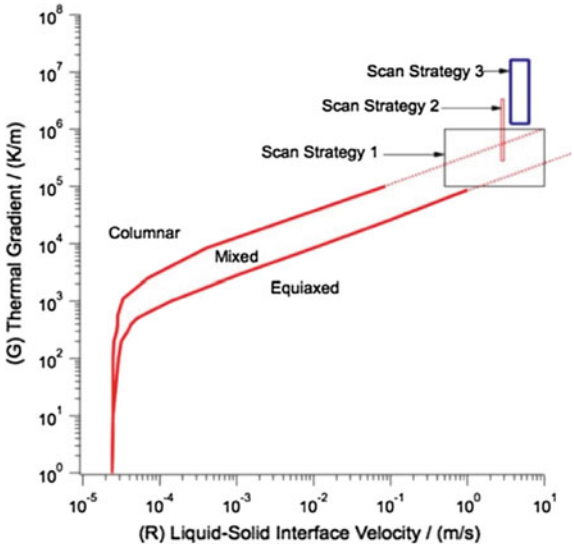


Fig. 1.17 Process used to control grain orientation by manipulating the thermal gradient with the liquid-solid interface velocity relative to an analytical model for Inconel 718 (Data compiled from Millikin 2014, Vehicle Technologies Office 2015)

they do not quantify the potential use and impact of this AM-specific ability. However, the research illustrates how parameters for e-beam or laser processes could be characterized to enable the integration of AM build parameters, and the corresponding material properties could be integrated into a CAD processes for material and component optimization in the near future.

AM is, for the first time, enabling site specific control of materials, processes and properties of the end product. While this is exciting, it reveals a number of big challenges and opportunities.

1.6 Challenges

In terms of challenges moving forward, additive manufacturing is rapidly enabling engineers to manufacture things they cannot design. In other words, the technology is rapidly outpacing the design tools. As with the microstructure control, systems are being developed that enable multiple materials, hybrid materials and compositionally or functionally graded materials. Design and analysis tools do not exist that can enable an engineer to design, optimize and analyze hybrid structures where there is complexity in both geometry and material. In the early 2000s, computer aided design tools began integrating design with finite element analysis. Emerging trends are showing that the next evolution of design tools will include manufacturing processes. The engineer will need computational tools embedded within the design tool to enable manipulation of the manufacturing process to control the properties of the components. We will no longer be restricted to single materials or isotropic material properties. Furthermore, we are beginning to see the first hybrid machines that combine multiple processes (additive and subtractive). These systems will evolve to enable automated pick and place of components within a single AM produced component. Over the next ten years, Additive Manufacturing will transform from production of components to production of systems. The ability to model, simulate and control these processes will rely on computational tools that do not presently exist on the engineer's desktop.

1.6.1 Design Tools

There is a growing effort focused on developing and standardizing DFAM methods just as was done earlier for computer aided design (CAD). However, what this means exactly is still up for discussion. Design for manufacturing (DFM) typically refers to the designer tailoring their designs to eliminate/minimize conventional manufacturing difficulties and minimize cost, much of which is attributable to fewer manufacturing defects and higher yields. Typically re-designs done for DFM are incremental designs. DFAM should follow the same trends but not allow design rules developed for SM become a constraint. Said differently, DFAM should employ true design synthesis because AM enables greater shape and material use complexity that is not possible using SM.

Each of the AM processes have limitations. First, AM is truly a discrete process. Layer heights and row widths are discrete. This discrete nature of the process can introduce unexpected, but predictable, defects in the components. For example, consider the construction of a thin, 70 μm thick, wall structure. If the row width, due to the focal diameter of the laser is 25 μ, this introduces a few interesting challenges. First, one could manufacture this wall three different ways:

- construct a solid 50 μ wall by constraining the outside surface and moving the inside surface adjacent to the outside surface,
- construct a solid 50 μ wall by constraining the inside surface and moving the outside surface adjacent to the inside surface,
- construct a 70 μ wall with a 20 μ gap.

One could try to fill the interior but it would be extremely difficult due to the size of the laser and potential buildup of heat impacting residual stress and microstructure. Clearly the designer must consider the process, and the control of the toolpaths from the slicing software, when manufacturing an AM component. Such realities and considerations need to become a standard part of DFAM tools.

AM processes are likewise anisotropic in terms of both geometric accuracy and material properties. From a geometric perspective, AM processes typically have far greater resolution in the horizontal plane than the vertical plane. As before, the layer height is discrete whereas the accuracy in the horizontal direction is controlled by the machine resolution. Gradual vertical inclines manifest themselves as a stair-stepping feature.

Likewise, many AM products exhibit anisotropic mechanical properties. This can be an opportunity or a challenge. As discussed earlier, the opportunity is that AM enables deliberate local variations in the as-deposited microstructure that impact mechanical properties. The challenge is that the anisotropy of the deposit complicates design by making it more difficult for the properties in all directions for meet requirements. Currently, this is being viewed by some designers as a new and additional constraint. In reality, anisotropic material properties in wrought products have been known for a long time and have been dealt with successfully. Two examples are:

- the tensile and other properties in the short transverse (ST) direction of high strength Al alloy plate are known to be lower. This is accommodated by orienting the component to minimize loading in the ST direction.
- The tensile and other properties of flat rolled Ti alloys are known to be different in the longitudinal (L) and transverse (T) directions. This is accommodated by orienting the component to utilize the stronger or stiffer direction beneficially or, as above, to minimize the loads in the direction with lower properties.

In the case of AM, the equivalent design solution is to plan the component orientation in the build to minimize the loads in the directions with lower properties.

1.6.2 Certification/Qualification

In terms of computing and data analytics, the greatest challenge today is rapid AM component certification and qualification. New insight into additive manufacturing components qualification and certification, process optimization and control, as well as rapid development and deployment of new materials can be gained by undertaking a data analytics approach. This approach relies on the combination of sophisticated system monitoring techniques, high fidelity physics based modelling and simulation, large volumes data analytics, and cutting-edge machine learning methods. For every component that is manufactured, all pre-processing information (modeling, simulations, processing parameters, toolpaths…), real time processing information (in situ imaging, processing measurements…) and post processing (heat treatment, ex situ imaging) must be collected, analyzed and cataloged (see Fig. 1.18) along with final component performance data (meets or does not meet requirements).

To date, the methodology for developing processing parameters for AM technologies has been based around process maps in which specific parameters relevant to the molten pool (bead) size are evaluated. Most approaches have identified key processing parameters to be: beam power, beam velocity, beam size or focus, bead hatch spacing, layer thickness, preheat temperature, etc. These parameters are 'optimized' on small coupons and then extended to full size components using an accurate transfer function. Once optimized, these parameter sets are applied to all different geometries fabricated in the process using predefined space filling algorithms. In conventional additive manufacturing technologies, the preferred scan strategies are snake infill, stripe patterns, or checkerboard based patterns. The fundamental challenge with this approach is the geometry of the component is not considered as a processing variable. However, it has been well documented that this approach can lead to components being fabricated with identical processing parameters, but having completely different pore morphology and distribution, location specific microstructural characteristics, and geometrically dependent properties (tensile, fatigue, toughness, etc.). With the current method of parameter development and infill pattern, the majority of the component is fabricated with steady state solidification and uniform thermal cycles. However, the steady state regimes are not typically the areas of the component that dominate the failure mechanisms as complex thermal transients initiated

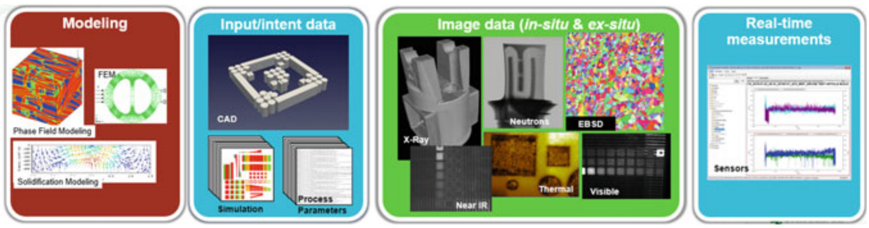


Fig. 1.18 Capture all design intent, processing and post processing information

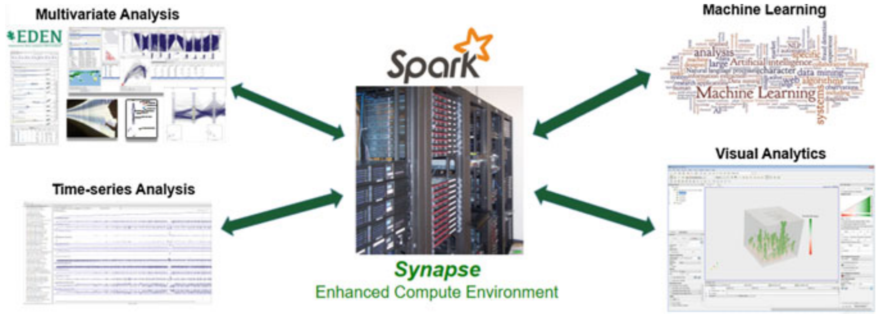


Fig. 1.19 Machine learning framework

as a function of geometry (non-steady state regime) are responsible for increased amounts of porosity and non-uniform solidification microstructures.

In order to emphasize the combined importance of geometry, scan strategy, and processing parameters on component quality, a data framework for housing and storing various AM data modalities including model output, AM process intent data, in situ monitoring data, and post inspection data. The framework has been based around DREAM3D, an open architecture, open source software platform and has demonstrated the ability to store spatial and temporal information from electron beam based AM builds. Although this has been an extremely important method for visualizing, analyzing and extracting build information, the software requires domain expert input from AM process and materials experts. The long-term goal of this program is to utilize advanced computational algorithms, machine learning and artificial intelligence based approaches to eliminate the need for a materials specific domain expert, leading to born qualified components (see Fig. 1.19).

The ability to rapidly validate and qualify components made by AM is crucial to adopting it for small lot production situations such as replacement components for out of production aircraft systems where the tooling used to make the original components by SM is no longer available. As outlined above, a key element in rapid validation and qualification is the availability of higher fidelity physics based models for properties using AM process parameters as variables.

1.7 Summary, Conclusions and Suggested Further Work

This paper describes an approach to light weighting and part count reduction of components enabled by additive manufacturing (AM), an emerging and potentially revolutionary manufacturing technology. As part of this description, an overview of the currently most effort-intensive AM processes is included. The ability to depart from incremental designs used to create components by conventional subtractive manufacturing (SM) is claimed to critical to the long-term success and breadth of acceptance of AM. Development of new design practices that we have called design for additive manufacturing (DFAM) are an essential part of this transition. The paper describes several examples where DFAM has been applied. AM also has the capability to locally alter the material microstructure. Today, design tools do not have the capability to capitalize on this capability to achieve improved component performance, better property-structure models coupled with improved design tools will permit this sometime in the future.

AM is now mature enough that its potential as a manufacturing game changer is clear, but there are still an number of areas that require improvement and maturation. These are described and discussed. Longer term, the breadth of application will depend to a significant degree on the successful development of high fidelity process-material property models. Such models figure centrally in shortened validation and qualification times for AM components. Coupled with the intrinsic tool-less nature of AM, there exists the promise of creating small numbers of components in days as opposed to months.

Clearly there are many technical issues to address in order to capture the full promise of AM. These have been mentioned in the text where appropriate. Included among these are the development and refinement of standard DFAM tools that have the capability to incorporate the improved component performance due to locally altered microstructure. These tools will need to be coupled with better high fidelity microstructure—property models. These models are also needed to enable rapid validation and qualification of AM created components.

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Chapter 2
Lightweighting and the Future of Aerospace Metals

Daniel Miracle

Abstract The search for low density, high strength alloys supports the perennial drive for lightweighting in the transportation industries. Improved efficiency is achieved through reduced mass or higher engine operating temperatures, and so materials with high temperature strength or high specific strength are both considered here. The first 100 years of powered flight gave the world spectacular innovations and capabilities, and metals played an indispensable role in these advancements. Recently, some have come to consider structural metals as a mature technology with limited opportunities for future innovations. However, a convergence of new tools and capabilities now offers new opportunities for metallic innovations, including computational alloy development, additive manufacturing, and reduced variability and uncertainty. A vast range of new alloy systems has recently been proposed and new alloy development strategies are exploring this expansive new alloy space. Here we present the challenges and opportunities for future innovations in aerospace metals.

Keywords Structural metals · Aerospace · Lightweighting · High temperature

2.1 Introduction

Since the birth of the aerospace age, metals have played an indispensible role in making spectacular innovations and capabilities possible. The first powered flight by the Wright brothers in 1903 relied on a crankcase of age-hardened aluminium to provide the needed power at low weight (Gayle and Goodway 1015). The first all-metal airplane was demonstrated in 1915, but wood and fabric dominated aircraft design and construction until the mid 1930s, after which the superior properties of metals made them the overwhelming materials of choice. Entire families of alloys have been developed around aerospace applications, including age-hardened aluminium, titanium alloys, specialty steels and nickel-based 'superalloys' for the most

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demanding high temperature applications. Aerospace metals simultaneously provide many required properties, including low density and high strength, good ductility and fracture resistance, ability to support fatigue and creep loading, and environmental resistance. Metallic materials are also formable, machinable, repairable and affordable, adding to their value.

Any moving system benefits from lighter weight components. Less energy is consumed in moving lighter systems, improving energy efficiency. Lighter parts also improve performance, since acceleration is faster in parts with lower mass. Light weight is especially important in aerospace applications, where the system not only moves but is also lifted from the ground—both inertia and gravity must be overcome. Lightweighting can be achieved by developing a lower density material with the same strength, by using a stronger material with the same density (since less mass is needed to support the same loads), or any combination of strength and density that gives a higher specific strength.

High temperature materials also improve energy efficiency since higher operating temperatures give more efficient power conversion. This is true for internal combustion engines, for gas turbine engines, and also for land-based power turbines that convert fuel to electricity. By improving overall engine efficiency, metals that increase engine operating temperature offer benefits similar to lightweight alloys regardless of the alloy's specific strength. High temperature materials are thus considered here along with lightweighting since they can provide similar benefits. Of course, an alloy that has both higher specific strength and a higher operating temperature is doubly impactful.

After a century of metals innovations that have enabled continuous improvements in aerospace capabilities, the pace of advances has slowed. New concepts for alloys with higher specific strength or higher operating temperatures have dwindled. The time and resources needed to discover, develop, manufacture and certify new metals for aerospace applications has become so long and expensive that many windows of opportunity are missed. Design innovations are much faster and can have large impacts on improving efficiency and performance—blade cooling is a common example. Non-metallic materials are now replacing metals in some of the most challenging applications. Graphite-epoxy composites continue to replace aluminium skins and ceramic matrix composites (CMCs) are poised to replace some nickel-based superalloy applications. Lower density and higher operating temperature make these new non-metallic materials very attractive in spite of higher cost. As a result of these trends, aerospace metals are considered by some to be a mature technology with little opportunities for future innovations.

A technology is mature only when there are no new ideas to pursue. In the last decade, many new concepts, capabilities and tools have been converging in the structural metals discipline and are poised to make significant changes in the way metals are discovered, developed, designed and manufactured. These new ideas include integrated computational materials science and engineering, additive manufacturing, advanced characterization methods that are reducing variability and uncertainty in properties, and fundamentally new alloying strategies that vastly expand the number of candidate alloy systems. Each of these technologies is briefly described in the present manuscript to discuss the challenges and opportunities in maintaining a robust, innovative environment in lightweight, aerospace metals.

2.2 Recent Metals Innovations in the Aerospace Industry

Here we briefly introduce recent metals insertions in the aerospace industry. These were emerging concepts ten, twenty or thirty years ago and may give insights into barriers that need to be overcome for successful technology transitions. As examples of recent lightweighting successes, these may also represent future lightweighting opportunities by using the same technologies in a broader range of applications. These may also illustrate the early application of new tools and techniques that are likely to play a role in future advancements.

2.2.1 Gamma Titanium Aluminide Alloys

Gamma titanium aluminide alloys are based on the intermetallic compound, TiAl. With densities from 3.8 to 4.2 g cm^{-3} (Westbrook and Fleischer 1995; Bewlay et al. 2016), TiAl alloys offer significant opportunities for lightweighting by replacing nickel superalloys with densities from 7.7 to 9.0 g cm^{-3} (Pollock and Tin 2006). Mechanical properties depend strongly on composition and microstructure, but room temperature (RT) yield strength typically ranges from 400 to 650 MPa and tensile ductility ranges from 1 to 3% (Westbrook and Fleischer 1995). The most widely used commercial alloy is Ti–48Al–2Cr–2Nb (atom %). Called 48–2–2, this composition does not require coatings for applications up to approximately 800 °C (National Research Council 2011). In the aerospace industry, 48–2–2 is used as low pressure turbine (LPT) blades in the General Electric GEnx™ engine that powers the Boeing 787 and Boeing 747-8 aircraft. Among many innovations in the GEnx™ engine, TiAl LPT blades contribute to a 20% reduction in fuel consumption compared to prior engines in the same class (Bewlay et al. 2016).

Success begets success, and wider use of TiAl alloys is expected in the aerospace gas turbine industry. A TiAl alloy with Nb, Mo and B (Ti–43.5Al–4Nb–1 Mo–0.1B atom %, called TNM) has recently entered service in the Pratt and Whitney PW1000G™ geared turbofan engine. TiAl LPT blades enabled this radical new engine design, which decouples the fan speed and the LPT speed, so that each can operate at their peak efficiencies. The PW1000G™ is used on the Airbus A320 neo aircraft. TiAl has been considered for other gas turbine applications, including compressor blades and shrouds, blade retainers and turbine dampers (Bewlay et al. 2016). In all of these applications, TiAl substitutes nickel superalloys that are nearly twice as dense as TiAl alloys. The relatively high cost of TiAl raw materials and manufacturing currently limits applications to high value-added uses, like those in the gas turbine environment. TiAl alloys have also been used in high performance automotive components, such as turbocharger rotors and valves for racing engines (Bewlay et al. 2016).

2.2.2 Aluminium-Lithium Alloys

Each weight percent of Li reduces the density of aluminium alloys by about 3% and increases stiffness by about 6% (Williams and Starke 2003), giving lightweighting opportunities for Al-Li alloys. Second generation Al-Li alloys have over 2 weight % Li but suffer from low ductility and fracture toughness, high anisotropy in mechanical properties and poor stress corrosion, limiting their applications. Third generation alloys such as 2095, 2195, 2097 and 2197 have overcome these technical problems by using less than 2 weight % Li. These new alloys have found wider acceptance, including the US Space Shuttle Super-Light Weight Tank and bulkheads and longerons in the F16 fighter aircraft (Williams and Starke 2003). In addition to weight savings from a 5% decrease in density over the initial aluminium alloy, the Al-Li alloys have much better fatigue performance, saving the US Air Force $21M over the entire F16 fleet.

Commercial applications have followed the early military insertions. Al-Li was first used in the Airbus A380 fuselage in 2006 and in wing skins in 2009, and is designed into the A350, Boeing 777 and 787 (Brothers 2016). Forged fan blades have been introduced in the PW1000G™ geared turbofan engine as the first rotating Al-Li hardware. These Al-Li fan blades are much thinner than graphite-epoxy composite fan blades, saving 10% in rotating weight, improving aerodynamic efficiency and giving a significant savings in production cost (Brothers 2016).

2.2.3 Beta Titanium Alloys

For over 60 years, titanium alloys have offered weight-saving opportunities in the aerospace industry. Perhaps the most widely known early application was in the SR-71 Blackbird aircraft. Designed to cruise at Mach 3, the skin temperature ranged from 200 to 300 °C, well beyond the capability of aluminium alloys. Candidate skin materials that could resist these temperatures included steel, nickel alloys and new titanium alloys. While broad generalizations are sometimes made regarding the specific strength of engineering alloys, the problem of lightweighting requires a closer look. Figure 2.1 plots the strengths of commercial alloys against density. Comparing the structural efficiency between different alloys is done with the aid of performance index lines—different loading conditions give lines with different slopes, s. Figure 2.1 shows performance index lines for uniaxial loading ($s = 1$), beam bending ($s = 3/2$) and panel bending ($s = 2$). These three lines are drawn through the strongest titanium alloy. Any competing alloy that lies above one of these lines is structurally more efficient than the best titanium alloy for the loading condition indicated, and can

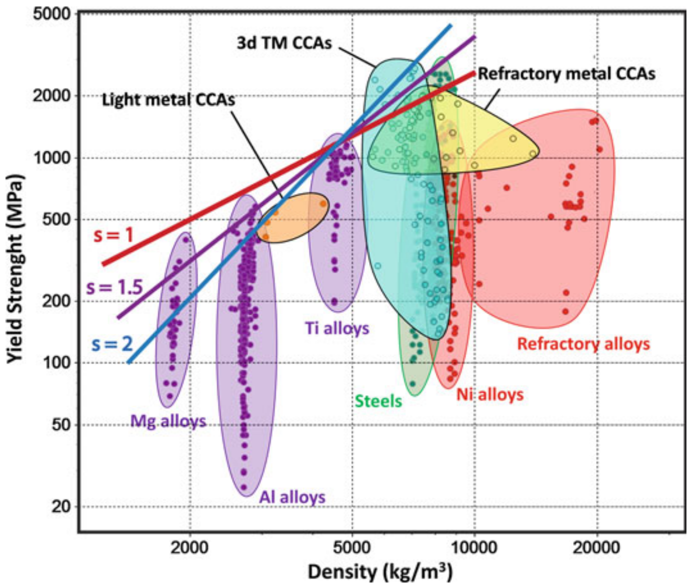

Fig. 2.1 Materials property space for room temperature yield strength versus density of conventional metal alloys and complex, concentrated alloys (CCAs). The lines give performance indices for uniaxial loading (slope, s = 1), beam bending (s = 1.5) and panel bending (s = 2). See the text for additional discussion of this plot. This chart was redrawn from Gorsse et al. (2017), and displays data for about 1220 commercial and 120 complex, concentrated alloys

produce parts with lower weight. From Fig. 2.1, some of the strongest steels are more structurally efficient than the best titanium alloy in uniaxial loading, titanium and steels are equivalent under beam bending, but titanium is better than nickel or steels in panel bending, the loading mode for aircraft skins. Aluminium and magnesium alloys are better choices for aircraft skins from the perspective of structural efficiency, but neither gives the temperature capability needed for the SR-71. In this particular application, a combination of titanium's strength, density, temperature capability and the loading condition result in lighter weight components.

Following this early success, titanium alloys have become important for a wide range of applications where temperatures exceed aluminium capabilities and would otherwise require heavier alloys. Titanium alloys are now used in gas turbine compressors, in engine pylons and in wing skin structures subjected to hot exhaust gases from turbine engines. Titanium alloys are also important for a wide range of heavily loaded aerospace applications such as bulkheads, wingboxes and landing gear. For example, forged and machined Ti-6Al-4V is used for the Boeing 747 landing gear beam (Williams and Starke 2003). More recent applications emphasize high-strength beta titanium alloys such as Ti-10V-2Fe-3Al (weight %, called Ti-10-2-3) and Ti-5Al-5Mo-5V-3Cr (weight %, called Ti-5553). Ti-10-2-3 is now used in commercial aircraft landing gear for the Boeing 777 (Williams and Starke 2003; Smith 2003). The strongest steels have inadequate fracture toughness or are susceptible to hydrogen embrittlement, and the best steel for the landing gear application, 4340, has strengths of 1800–1900 MPa (Williams and Starke 2003). Ti-10-2-3 is heat-treated to 1250 MPa, giving a clear advantage over 4340 in beam bending (Fig. 2.1) and thus saving significant weight. Although aluminium and titanium alloys are structurally equivalent in beam bending, aluminium landing gear would be larger and would not fit in the available space (Williams and Starke 2003). Thus volume can also be a limiting consideration.

2.3 The Future of Aerospace Metals

A convergence of new technologies, new tools and new alloy concepts are changing the way metal alloys are conceived, developed and certified for application. The most significant approaches are briefly described here. Both the benefits and the challenges associated with each topic will be discussed.

2.3.1 ICMSE

Integrated computational materials science and engineering (ICMSE) was recognized as a new discipline that was still in its infancy in a seminal report issued by the US National Research Council (National Research Council 2008). By harnessing the power of computer models, approaches are being devised to accelerate the discovery and development of new materials. This requires linking physics-based models of materials behavior at vastly different length scales with computer-based engineering design tools and with experiments. When done well, this methodology dramatically narrows the number of candidate alloys, microstructures and processes and promises to reduce the current overwhelming reliance on extensive, redundant testing. Testing remains an essential step in the materials innovation infrastructure, and the US Materials Genome Initiative, established to implement the ICMSE methodology, describes three inter-connected themes: computational tools, digital data and experimental tools (Ad-hoc Interagency Group on Advanced Materials 2011). The selective use of existing test methods must be complemented with test methods not traditionally used in structural metals. While the MGI report mentions high throughput experiments, the strong dependence of mechanical properties on microstructure and on length scales that are not typically available in thin film materials libraries challenges conventional high throughput methods for structural alloys. Nevertheless, new high-throughput concepts are being conceived to tackle these challenges and new strategies are being devised to couple computations and high throughput experiments to accelerate alloy discovery and development (Miracle et al. 2017). The ICMSE approach is already showing success, and is expected to offer new options for lightweight or high temperature structural metal alloys.

The benefits associated with a robust ICMSE capability are enormous. In one application alone, the ICMSE design and validation of an improved turbine rotor gave a projected savings of $200M (National Research Council 2008). In spite of this large payoff, the ICMSE methodology has not been implemented in a more pervasive fashion, underscoring the substantial challenges that must still be overcome. Detailed discussions of both technological and cultural barriers are given in (National Research Council 2008). The technical needs include a range of computational capabilities (improved scalability of parallel processing, higher communication bandwidth between processors, servers and storage; better graphics hardware; intelligent reduction of information for passing to the next level of modeling) along with uncertainty quantification of the models used (including propagation of uncertainty) and visualization of results. The cultural and organizational barriers are equally significant in the engineering design, industrial materials engineering, and manufacturing communities. A shifting role for materials science and engineering professionals is also required. Each of these are discussed in detail in (National Research Council 2008).

2.3.2 Additive Manufacturing

While other lightweighting approaches involve development of new materials with higher specific strength or operating temperature, additive manufacturing (AM) offers weight reduction through new component designs. The design of complex-shaped parts or assemblies is currently constrained by the ability to manufacture or assemble those parts. This often results in sub-assemblies of many simple-shaped parts that are then joined to produce the final unit. Joints are often weak spots in a structure and so require additional mass to offset the poorer structural efficiency. Fasters also add to the mass of assemblies. Even in single piece components, conventional manufacturing can result in more mass than is needed—the extra mass is a byproduct of the inability to manufacture only the required details, or to economically remove unneeded mass via machining or other techniques.

By removing current design-for-manufacture (DFM) and design-for-assembly (DFA) constraints, AM enables a unitized construction philosophy that has already been established in graphite/epoxy composite components in the aerospace industry. With graphite/epoxy structures, unitized construction is an imperative to eliminate costly and structurally inefficient joints and to offset the high material cost by reducing touch labor associated with assembly. AM of complex-shaped metal assemblies not only can significantly reduce weight, but also reduces cost by significantly reducing or eliminating assembly operations. AM also offers new possibilities in topology optimization, including a wider use of conformal shapes and cellular structures to reduce unnecessary mass.

The potential benefits are substantial, and progress is already being made in the design and application of AM components. However, the technical challenges are equally daunting, and a great deal of progress is yet required to offer a broader range of benefits. The challenges in controlling composition, microstructure and defects in metal-based AM are well-known (Frazier 1917). Significant additional work is also required to fully utilize the design options offered by AM. Designers must learn to avoid current design practice and limitations that come from DFA and DFM concerns. They must become familiar with new tools to pursue topology optimization, new principles concerning material distribution and new concepts associated with hierarchical design. While AM is free from many of the limitations of conventional manufacturing and assembly, it nevertheless has its own inherent limitations. These must be defined, understood and reduced to standardized design practice (Kranz et al. 2015).

2.3.3 Reduced Uncertainty and Variability

Conventional engineering design practice often treats all of the material in a given component as homogeneous with the same properties throughout. However, the microstructure and properties in a part can vary due to location-specific differences in thermo-mechanical processing conditions such as deformation strains, strain rates, temperatures, cooling rates, defect populations and residual stresses. For example, the properties of the same turbine disk alloy are different in the rim and the bore due to different microstructures that result from different forging strains and thermal histories during manufacture. For many years, this variability was treated as an uncontrolled, statistical uncertainty in materials properties. Common design approaches use the minimum rather than average alloy properties as a practical approach to deal with this uncertainty. The margin between minimum and average properties thus represents the degree of uncertainty that comes from location-specific variability in microstructures and properties produced in a given manufacturing practice.

Significant advances in basic understanding of the relationships between processing, microstructures and properties, and the reduction of this knowledge to practical materials models, now gives better prediction of location-specific microstructure and properties. Further, new materials characterization tools and techniques now enable more accurate measurement of location-specific chemistry, microstructures, defects and properties. Such characterization tools include micro-pillar testing for local strength and compressive ductility, energy dispersive spectroscopy (EDS) for local chemistry, electron back-scattered detectors (EBSD) for local crystal structure and orientation, and an expanding ability to measure microstructural information in three dimensions (3D).

As an example of these new capabilities, a microstructure can be measured in 3D, giving a virtual, digital representation of the actual microstructure. This virtual microstructure gives the details of critical features such as the sizes and shapes of grains and pores or the size, location and frequency of micro-textured regions (MTRs). The digital representation of the 3D microstructure can be subjected to simulated loading, and the defects and microstructural features associated with deformation and failure can be identified. Similar loading histories can be applied to different virtual microstructures with equivalent statistics for the sizes and shapes of critical features, giving a more robust identification of critical features. These results can be validated with parallel experimental studies. Process modeling can be used to explore different process conditions in an effort to suppress the deleterious microstructural features. The actual 3D microstructures can be used to build virtual materials with equivalent statistics, which can be used as proxies to explore the response in different loading conditions, and to explore virtually the effects of changing the microstructural statistics.

These used to be research-only tools, but are becoming much faster through automation and are increasingly finding their way into mainstream use. Together, they give an improved ability to measure and model location-specific defects, microstructures and properties, reducing uncertainty and allowing a material to be used closer to its intrinsic capability. These reduced margins support lightweighting by reducing unnecessary mass.

2.3.4 Advanced Developmental Alloys

Developing new alloys with higher specific strengths or higher operating temperatures has always been a primary approach for lightweighting. While cost reduction is a major objective for many alloy development activities, lightweighting approaches continue to be pursued in all major aerospace alloy classes. Al-Mg-Sc alloys have been considered for many years but the high cost and limited availability of Sc have blocked major applications. Nevertheless, Al-Mg-Sc alloys are 4% lighter than 2024 Al and can be laser-welded, further reducing weight by removing material needed to support rivet joints (Brothers 2016). Timetal® 575 and Timetal® 639 are developmental alpha-beta titanium alloys with temperature capabilities and densities of Ti-6Al-4V but with higher yield and ultimate strengths (Hewitt et al. 1919). Timetal® 575 is being considered for future forged fan discs, and Timetal® 639 is a candidate for potential use as solid or hollow fan blades.

In nickel-based superalloys, a disordered, solid solution FCC γ phase is strengthened with atomically coherent intermetallic Ni_3Al precipitates with the $L1_2$ crystal structure (called γ'). It was recently discovered, in 2006, that an analogous microstructure and phases could be produced in Co-Al-W alloys. The W stabilizes the $L1_2$ Co_3(Al,W) phase, which is unstable in the binary system. While the density of these alloys is slightly higher than nickel-based superalloys, it may be possible to increase the maximum operating temperature, providing improvement in the overall propulsive efficiency. Significant exploratory work is underway on this new concept to produce an alloy that satisfies all the other properties requirements while enabling higher use temperatures. Replacing some of the W with lower-density Ti can reduce alloy density (Zenk et al. 2014), and more recent work has shown that W can be removed altogether when adding Mo and Nb (Makineni et al. 2015).

Conventional alloys are devised by selecting a base element with primary properties that approach the desired alloy properties, such as low density, high strength, good corrosion resistance or acceptable cost. Conventional alloy development seeks to optimize the full range of required properties by adding relatively small amounts of other elements. This approach has been pursued extensively for at least the past 100 years. While there is still room for important improvements, it is becoming increasingly difficult to discover new alloys with sufficient improvement in properties to offset the cost and risk of development and insertion.

A new concept has recently been proposed that forms an alloy base by combining three or more elements, and sometimes as many as eight elements, at high concentration levels. Called complex, concentrated alloys (CCAs) or high entropy alloys (HEAs) or multi-principal element alloys (MPEAs), this new alloying strategy vastly expands the number of alloy systems. Considering new alloy systems with between 3 and 8 elements, there are a total of 1.36×10^{10} alloy systems from the 72 metallic elements that are not radioactive, noble gases or halogens. Each alloy system can produce a large number of alloy bases by relatively large shifts in the concentration levels of the base elements. Finally, each alloy base has an immense number of discrete alloys that are produced by relatively minor alloy additions as is done for conventional alloys. The number of unexplored alloys offered by this new strategy is truly cosmic.

This new class of alloys is already producing unique and unusual properties, including exceptional cryogenic toughness, high work-hardening and the potential for higher use temperature relative to superalloys (Miracle and Senkov 2017). Due to the extra degrees of freedom in selecting alloy properties by choosing the principal elements, CCAs can also fill the properties spaces between conventional alloy bases, see Fig. 2.1. CCAs based on 3d transition metal elements (3d TM CCAs in Fig. 2.1) not only provide properties between titanium alloys and nickel alloys or steel, but they also have higher structural efficiency than any of these three conventional alloy families for uniaxial ($s = 1$), beam bending ($s = 1.5$) and panel bending ($s = 2$) loading modes. While the refractory metal CCAs do not seem attractive in Fig. 2.1, a similar plot at 800 and 1000 °C show promise to expand use temperature with this new class of alloys (Gorsse et al. 2017).

The work in CCAs is still in its infancy. The vast number of new candidate alloy systems is the most attractive feature of this concept, but it also represents the most significant technical barrier. With so many options and possibilities, it is difficult to rationally select a particular combination of primary elements as a new base alloy system for study. Stated differently, it is exceptionally challenging to decide a priori how many and which principal elements will have the best chance of achieving a particular set of required properties. The vast number of possibilities also makes conventional approaches of alloy screening hopelessly inadequate. To address these concerns, new search strategies that integrate high-throughput computations with new high-throughput experiments tailored to address the unique challenges posed by structural materials have been proposed (Miracle et al. 2017). Advancements in developing these new tools and in applying new strategies will not only accelerate the exploration and discovery of new CCAs for lightweighting, but will also accelerate alloy development for other purposes as well.

2.4 Summary

The present manuscript describes a number of new concepts that offer opportunities to reduce system weight or to increase the operating temperature of propulsion systems, both of which can improve the overall efficiency of transportation systems. These new concepts cover the full spectrum of topics in materials science and engineering. New computational methods are accelerating alloy exploration and development, enabling the discovery of new alloys and microstructures with higher specific strength or higher operating temperature. New manufacturing methods, especially additive manufacturing (AM), permit more efficient, lighter weight component designs that are no longer limited by processing or assembly constraints. Improved materials models are being integrated with advanced materials characterization techniques to reduce uncertainty in location-specific properties of components, leading to weight reduction through the safe and reliable use of materials closer to their actual capability. New ideas for improving conventional alloys are approaching readiness for certification and application, and entirely new alloy design concepts open a cosmically vast range of new alloy compositions for future study.

The recent lightweighting insertions described in this paper illustrate that ‘recent successes’ don’t happen overnight. Two or more decades have been required in the past to move from initial concept to commercial application. The new technologies described here are at different levels of maturity, and significant additional work is needed in each area to mitigate risk and to establish these new tools and alloys as commonly accepted. Nevertheless, initial successes of these ideas have already been achieved, validating the potential for future improvements in lightweighting.

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Chapter 3
Exploring the Trends, Opportunities and Aluminum Solutions Behind Automotive Material Innovation

Todd Summe

Abstract For automakers, staying competitive has never been more critical. The evolving mobility ecosystem will ultimately be determined by consumers' demand for cost, convenience and connectivity—creating opportunities for automakers, technology firms and material suppliers to deliver new innovations. In parallel, automakers continue to seek advantages in safety, fuel economy and vehicle performance through lightweighting, leading vehicle designers to seek optimized multi-material body structure solutions.

3.1 Overview

For several years now, the automotive industry has been in the middle of a significant shift in design, engineering and priorities to improve vehicle efficiency due to stricter regulations and consumer demand. The innovation required to continue to advance this light-weighting technology represents significant hurdles, and suppliers of lightweight materials need to collaborate with car companies to clear those hurdles in a robust and efficient manner.

It's an exciting time for the aluminum automotive supply business today. Aluminum solutions have been around for a long time, but now the adoption rate is accelerating across high volume platforms like the Ford F150 and many others. The adoption for high volume, smaller vehicle platforms is also accelerating. The whole industry is in great demand for aluminum solutions with advanced characteristics for strength, formability, joining and finishing.

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3.2 Agenda

Automotive manufacturing is becoming a multi-material world, where partnerships are key to success. Aluminum will play a significant role in next-gen vehicle design, and the industry is committed to developing the innovations and technologies that assist automakers in meeting their current and future needs. In exploring these evolutions, the presentation will cover the following subjects:

- Section 1: Expectations for Automotive Material Suppliers
- Section 2: Aluminum Adoption and Demand
- Section 3: Marketplace Trends
  - Global Marketplace
  - Global Legislation
  - Electrification
- Section 4: Collaboration with Automakers
  - Collaboration with Ford
  - Multi-Material Designs in the Cadillac CT6
- Section 5: Future Vehicle Design
  - Increased Strength and Safety
  - Joining Solutions
  - Integrating Aluminum into Electric Vehicle Designs
- Conclusion and Outlook for the Future.

3.3 Expectations for Automotive Material Suppliers

3.3.1 Global Automotive Footprint

The global automotive market requires material providers to have a global presence with globally available products and services. Novelis has invested significantly to achieve such a presence with a uniquely global automotive product line with premium automotive sheet in Asia, Europe and North America (Fig. 3.1).

3.3.2 Sustainability and Recycling Leadership

With a growing focus on efficiency and sustainability throughout manufacturing supply chains, automotive material suppliers must consider recycling in their product development and service offerings to OEMs and tiers, see Fig. 3.2.

Fig. 3.1 Novelis's presence in the global market for automotive sheets

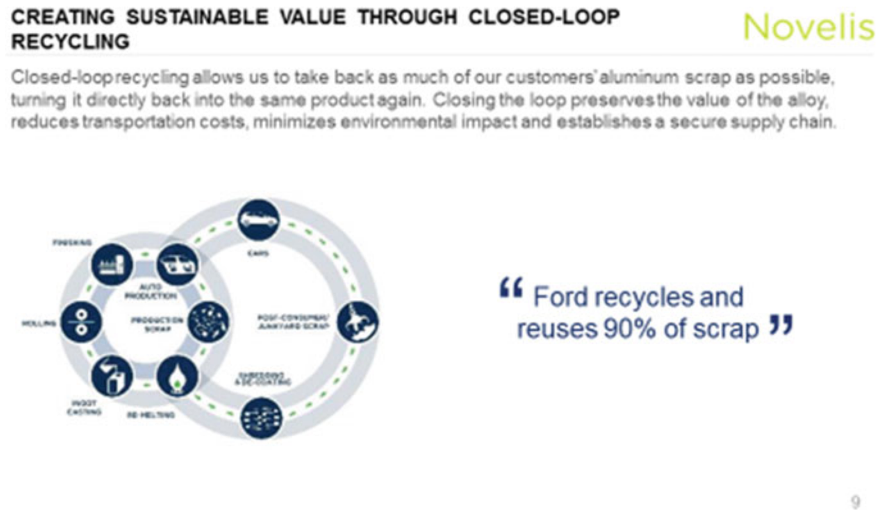


Fig. 3.2 Role of close loop recycling in sustainable manufacturing of automotive components

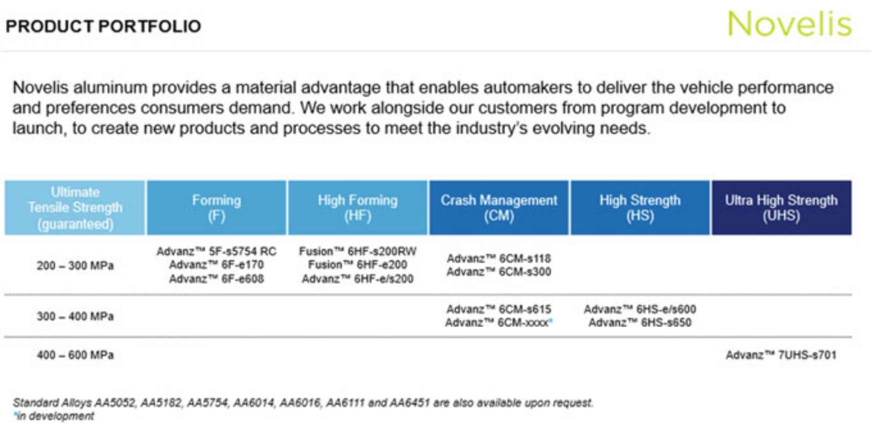
Novelis has also invested significantly in becoming the global leader in aluminum recycling. Through collaboration with Jaguar Land Rover and transport partners, Novelis established the first closed-loop system with a dedicated round-trip railway service to efficiently deliver material between locations in Germany, Switzerland and the United Kingdom. This service has resulted in an 80% reduction in CO_2 equivalent emissions compared to standard road transport.

In North America, Novelis and Ford developed the world's largest closed-loop recycling system for their most popular lineup of aluminum-intensive trucks. As a result, Ford recycles and reuses more than 90% of scrap—enough to produce 30,000 F-150 bodies each month.

3.3.3 Automotive Product Portfolio

As OEMs and tiers are early in the adoption of aluminum in automobile body structure, it is important to make this transition manageable from an engineering and production complexity perspective.

This summary shown in Fig. 3.3 illustrates the Novelis product portfolio that is available in every region. As you can see, the emphasis is on products that are specifically designed for each application segment but also balanced with products that are robust enough to cut across multiple application segments. These cross cutting alloys simplify the transitions to a new material system for the automakers and the entire supply chain.



PRODUCT PORTFOLIO

Novelis

Novelis aluminum provides a material advantage that enables automakers to deliver the vehicle performance and preferences consumers demand. We work alongside our customers from program development to launch, to create new products and processes to meet the industry's evolving needs.

Ultimate Tensile Strength (guaranteed)	Forming (F)	High Forming (HF)	Crash Management (CM)	High Strength (HS)	Ultra High Strength (UHS)
200 – 300 MPa	Advanz™ 5F-s5754 RC Advanz™ 6F-e170 Advanz™ 6F-e608	Fusion™ 6HF-s200RW Fusion™ 6HF-e200 Advanz™ 6HF-e/s200	Advanz™ 6CM-s118 Advanz™ 6CM-s300		
300 – 400 MPa			Advanz™ 6CM-s615 Advanz™ 6CM-xxxx*	Advanz™ 6HS-e/s600 Advanz™ 6HS-s650	
400 – 600 MPa					Advanz™ 7UHS-s701

Standard Alloys AA5052, AA5182, AA5754, AA6014, AA6016, AA6111 and AA6451 are also available upon request.
**in development*

Fig. 3.3 Novelis's product portfolio

3.3.4 About Novelis

Novelis is a part of the Aditya Birla Group and is the world's largest producer of automotive aluminum sheet, with an estimated 50% market share.

- The #1 producer of flat-rolled aluminum sheet
- More than 40 years' experience in the automotive market
- More than 120 automotive-specific patents
- More than 225 vehicle models launched with our products around the world.

3.4 Aluminum Adoption and Demand

First, let's look at the material market with a focus on aluminum. Automakers have been trying to lower the average weight of their vehicles by partially substituting steel with lighter materials.

This has allowed for a greater application of materials such as aluminum, magnesium and plastic composites in automobiles.

Historically, steel accounted for close to 60% of the weight of the average North American automobile until recently. Aluminum-intensive vehicles, such as light trucks, SUVs and electric vehicles will continue to grow at a faster rate than the overall market in North America, Europe and China. According to a study by consulting firm Ducker Worldwide, the share of aluminum in the average North American lightweight automobile is set to rise to 16% (565 lb per vehicle) in 2028 from around 10.4% (397 lb per vehicle) in 2015. Since aluminum is lighter than steel, its share by volume would rise by an even greater amount (Fig. 3.4).

3.5 Marketplace Trends

For automakers, staying competitive has never been more critical. We work in a global marketplace, and while diverging emission regulations are challenging for developing global vehicle platforms, electrification trends are changing consumer behaviors and vehicle designs. The entire marketplace for automakers is changing at an increasing rate, and material suppliers, to remain relevant, must facilitate the OEMs response.

3.5.1 Global Marketplace

The automotive market is a global marketplace, as illustrated in Fig. 3.5. Today, the automotive supplier industry is a growth engine for the global economy, creating

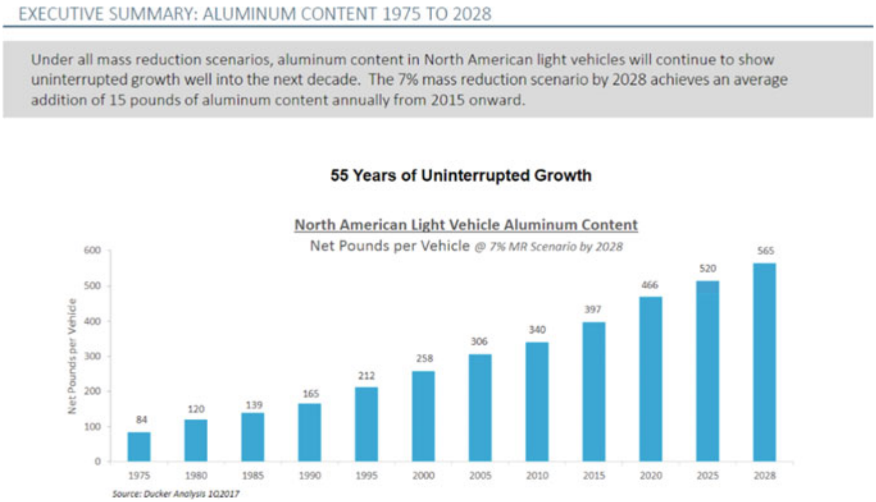


Fig. 3.4 Growth of aluminium product utilisation in automotives

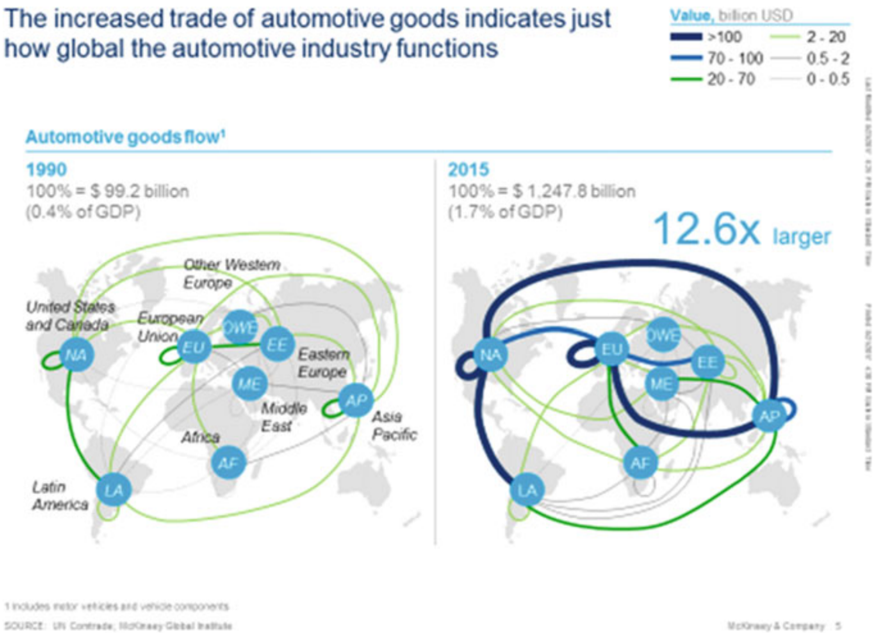


Fig. 3.5 The spread of the automotive goods industry across the world

value, jobs and breakthrough innovations worldwide. From 2004 to 2014, suppliers contributed over half of the innovations found in cars today.

The last decade has brought significant change to the automotive supplier industry, and even more transformative change is on the way. As you can see by the information provided by consulting firm McKinsey, the increased trade of automotive goods indicates the scale of the global automotive industry.

China's emergence as the world's largest automotive market is fueling a burgeoning domestic auto industry to compete alongside more established global players. For decades, Japanese, North American and European OEMs formed a group that, at its height, produced an overwhelming majority of the world's automobiles. South Korea has since taken its place among the automotive leaders, capturing over 10% of the world market in the past 15 years.

As automakers continue to move toward product efficiency and demand increases across the world, automotive material suppliers must be prepared to work with all automotive manufacturers no matter where they are.

3.5.2 Global Legislation

Global legislation is mandating a reduction of carbon emissions and the development of the electric vehicle infrastructure, which will drive OEMs to light weight.

In China, the increasingly strict regulations on emissions call for a combination of innovative energy saving and emission reduction solutions, bringing more opportunities for lightweight materials suppliers.

As global legislation mandates stricter emissions standards and OEMs continue to seek light weighting vehicle solutions, particularly for the light truck and electric vehicle categories, automotive aluminum is a material of choice that can compete with steel and welcomes collaboration to serve the next generation of vehicles.

3.5.3 Electrification Grows Need for Lightweighting

The growth in electrification will further prompt the need for weight savings and the use of aluminum. Energy efficiency is a critical performance metric for electric cars, and lightweighting is one of the most effective options to improve the energy efficiency of any vehicle, including electric ones (Fig. 3.6).

3.5.4 Electrification Creates New Requirements in BIW

For the Mercedes-Benz EQ, additional influences to e-mobility come from the changes in BIW requirements. As you can see from this example (Fig. 3.7), there are

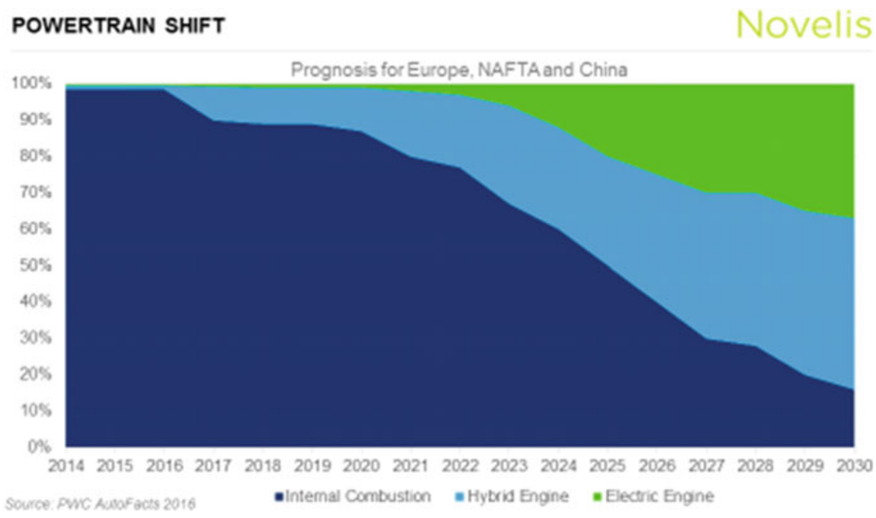


Fig. 3.6 Trends in automotive engines: Internal combustion versus hybrid versus electric

Fig. 3.7 New requirements of body-in-white in electric cars

several physical (in green) and functional (in orange) requirements that will impact vehicle designs in the years ahead.

3.6 Collaboration with Automakers

The use of aluminum in vehicles has enabled automakers to drive more innovation throughout the vehicle via secondary system down-sizing and other means. Early stage collaboration with automakers enables advanced vehicle planning based on the confidence that material suppliers meet advanced performance targets consistently. This ability to deliver consistent, high-quality products from prototype testing to large production quantities allows automakers to maximize their production and meet the demand of the mass market.

We are already seeing aluminum penetration in body-in-white based on the lightweighting benefits of the material and its positive impact on vehicle design and safety. For aluminum-intensive vehicles to outperform previous generation body styles, automakers collaborate with material suppliers to produce innovative high-strength products. Novelis partnered with Ford to enable a completely redesigned F-150 in order to reduce the vehicle's weight and increase fuel efficiency and payload. A brand new aluminum product, Advanz™ 6HS—s615, was developed by Novelis scientists and engineers. This innovative alloy is formable enough to withstand high volume part stamping and assembly, yet strong enough to meet rigorous durability and safety requirements.

To create Advanz™ 6HS—s615, the toughness in bending was increased by 33%, creating a new industry benchmark for strength and toughness.

3.6.1 Multi-material Designs in the Cadillac CT6

The CT6 is an aluminum intensive vehicle that General Motors (GM) approached with a multi-material optimization strategy (Fig. 3.8). This enabled them to achieve a leap forward in luxury and performance body design, receiving industry accolades from around the world.

GM designers studied the material selection for every part, and each material won its way onto the vehicle by being the best value solution for that part's function within the complete body. The material mix of CT6 is an excellent example of future body design: OEMs choosing the right material for every part, rather than adopting a single strategy for the whole vehicle body or major sub-assemblies.

This picture shows the mixed material architecture combining multiple aluminum alloys, boron and other steels. Based on the available materials at the time, AHSS and PHS was selected for the greenhouse and A and B-pillars to maintain integrity of the safety cage, with closeouts provided in lower-strength steel to limit noise in the passenger compartment. Aluminum was selected for the outer panels, closures and front and rear structure. However, within each module, individual parts could be aluminum and steel depending on merit.

CT6 is lighter than its direct competitors Mercedes S-Class and BMW 7 series despite being larger than the S-Class and avoiding high-cost carbon fiber in the 7

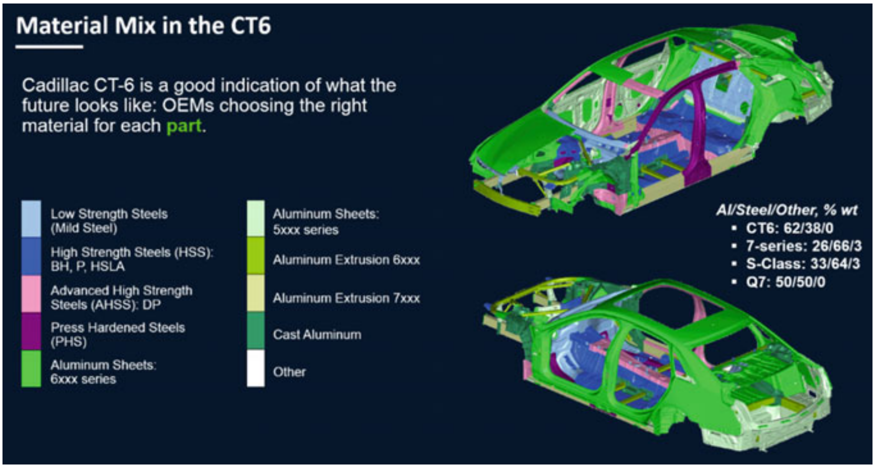


Fig. 3.8 Material mix in GM's aluminium intensive car

series. It is expected that the CT6 body-in-white has lower manufacturing costs than its competitors with fewer joining spots and still achieved a better bending frequency than the competition due to intelligent material mix and distribution. The CT6 has a 62% aluminum body by weight.

3.7 Future Vehicle Designs

Working alongside automakers from research, advanced engineering and program development to launch, material suppliers are able to create new alloys and manufacturing processes to meet evolving customer needs. Through research and collaborative development, aluminum suppliers are bringing new products and processes to market that offer a safe, sustainable and cost-effective way to increase fuel economy and reduce CO_2 emissions.

3.7.1 Integrating Aluminum into Electric Vehicle Designs

Today, electric vehicles are more expensive than traditional vehicles, mainly because of the cost of batteries. It is therefore important to make electric cars as energy efficient as possible. Lightweighting is one of the most effective options to improve the energy efficiency of any vehicle, including electric ones.

Fig. 3.9 New features in an electric vehicle NIO ES8, that use Al alloys extensively

Each new vehicle model presents a unique challenge to automakers. To help answer new design challenges, teams of specialists assess the mechanical properties, design flexibility and range of fabrication alternatives needed to realize next-generation vehicles.

In April, NIO, a next-generation automaker, unveiled the NIO ES8 for the China market and is planned for serial production in late 2017. The ES8 has an all-aluminum body and chassis, front and rear motors with electric all-wheel drive and active air suspension (see Fig. 3.9). The vehicle's swappable battery will provide a charging experience that surpasses refueling at gas stations.

Through a long-term partnership, NIO will leverage the unique properties of high strength, lightweight aluminum alloys to design a lighter, better performing and more energy-efficient vehicle. Over the next five years, NIO will launch multiple electric SUV models using automotive aluminum solutions.

Leveraging Novelis' global products and manufacturing, NIO will draw supply from the Changzhou plant—China's first facility dedicated to heat-treated automotive sheet. Local expertise and supply is key to expediting NIO's production schedule at a time when automakers face mounting pressure in China to increase electric vehicle production. As aluminum becomes increasingly integrated into autonomous and electric vehicle designs, the partnership with NIO will showcase the state-of-the-art benefits of automotive aluminum.

By leveraging advanced aluminum products, NIO is pushing the limits of what is possible with electric vehicles from both a performance and design standpoint. This innovation partnership demonstrates the importance of being more than just a material supplier. Long-term collaboration, integrated problem solving and a close working relationship between material suppliers and automotive design teams helps ensure vehicles are built to maximize the unique attributes of aluminum and meet the mobility demands of the future.

3.7.2 Increased Strength and Safety

The aluminum industry is producing new advances in formability, but the most requested customer innovations are for increased energy absorption and strength for enhanced safety. And, as mentioned with the CT6 example, automakers are increasingly in need of innovations developed for mixed-material solutions. Automotive development engineers are looking for the best value solution for a part's function.

Current automotive aluminum product development priorities fall into the following categories:

- 6xxx alloys for high strength and crash energy management applications
- 6xxx alloys for enhanced forming of closure system applications
- 7xxx alloys for ultra-high strength applications
- Engineered surface solutions for enhancing forming, joining, finishing and durability.

Each of the product families listed above can be robustly formed into shapes and features for structural or exterior applications but at 50–60% of the weight compared to their steel counterparts. Each of these new alloy systems fit into established automotive forming and body-shop manufacturing systems with relatively minor modifications. That said, there are updates to process equipment and procedures required to facilitate the most mass-efficient and cost-effective solutions for high volume production. The presentation will provide examples of this.

Figure 3.10 shows the mass-specific strength of aluminum and steel alloys as an indicator of weight saving potential.

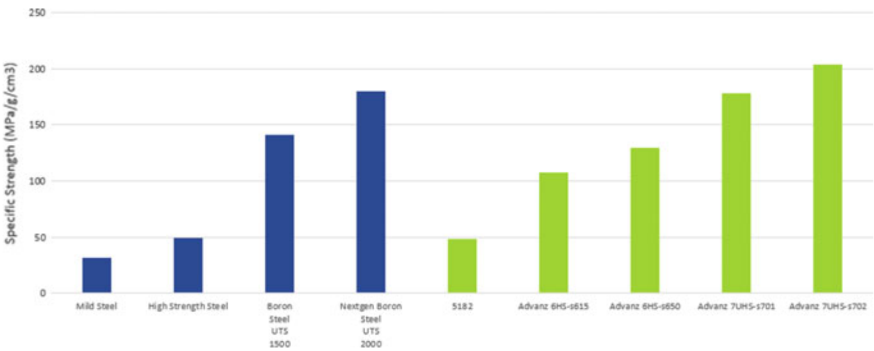


Fig. 3.10 Mass-specific strength of aluminum and steel alloys

Conventional room temperature forming is predominantly utilized for the majority of components. For 7xxx series alloys, the same basic hot forming flow paths that have been established for boron steel can be utilized.

3.7.3 *Joining Solutions*

In vehicle manufacturing engineering, the search for the "best way" to join components into subassemblies is a major part of the job. For conventional steel bodies, resistance spot welding has been the method of choice for decades. With the increased aluminum content in the body construction, automakers are adapting and developing additional joining methods for the body. The aluminum industry, including Novelis, is collaborating with automakers to develop low-cost aluminum and multi-material joining technologies that will make vehicle production even more economical. These include:

- Resistance Spot Welding
- Conventional and Remote Laser Welding
- Self-Pierce Riveting
- Flow Drill Screws
- Many of the methods listed above are used in conjunction with adhesive bonding.

Much of the material innovation focus is on creating optimized compositions and surface characteristics that enable all of these joining methods such that automakers have the flexibility to optimize for their structural performance and manufacturing process. The Fusion™-based product shown in the figure is one illustration of optimizing the surface layer for advanced joining. In this example, the product was designed specifically for remote laser welding, significantly increasing the joining speed relative to conventional laser welding (Fig. 3.11).

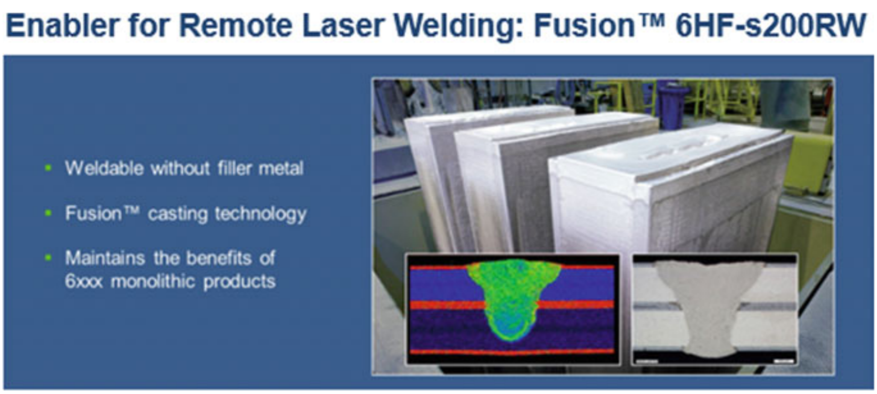


Fig. 3.11 Remote laser welded components for automotives increasing production speed

3.8 Conclusion and Outlook for the Future

For automakers, staying competitive has never been more critical. The evolving mobility ecosystem will ultimately be determined by consumers' demand for cost, convenience and connectivity—creating opportunities for automakers, technology firms and material suppliers to deliver new innovations. In parallel, automakers continue to seek advantages in safety, fuel economy and vehicle performance through lightweighting, leading vehicle designers to seek optimized multi-material body structure solutions. The vehicle body architectures, joining method advancements and design methods will enable efficient utilization of multiple materials throughout the body.

The aluminum industry, as well as other materials industries, must embrace the future of ever increasing demand for innovation that moves beyond the conventional assumptions of strength, forming and joining, especially as it pertains to the use of each material for the optimal function within the vehicle. The industry must continue to focus on elevating the performance, and value, of each new material but also on the effectiveness and efficiency of integrating with the dis-similar materials in a total vehicle and manufacturing systems approach. This approach must also include closed loop systems that maximize total efficiency and life cycle benefits. With the increasing pace of vehicle and mobility system evolution, the benefits of aluminum solutions will continue to increase and aluminum industry leaders, such as Novelis, are poised and committed to support the global automotive industry with innovation.

Chapter 4
The Role of Materials Engineer in the Product Cycle: A New Outlook

Mohamad S. El-Zein

Abstract The role that a materials engineer did and will be playing today and in the future is examined through a new outlook at function, education, training, project management, and collaboration. The need for this collaborative role through adjacencies' knowledge is driven by the reliance of the industry on subject matter experts in light weighting, value addition, and cost optimization. Naturally, when looking at AL, for example, the assumption is that materials engineers know the design, analysis, experimental testing, supply chain, etc. This, however, assumes that a function is an engineering department, and not a single competency domain and is driving a different enterprise dynamics. A case will be showcased as to show this role change and how to drive the education system and the enterprise to redefine the engineering roles and functions.

Keywords Adjacencies · Materials · Lightweighting · Design · Spider charts

4.1 Introduction

Traditionally, engineering is divided into silos of competencies where the role of materials engineer is in the domain of materials selection and failure analysis. However, the natural dependency of the design cycle and the supply chain forces one into boundaries unchartered before with new skills requirement. This in turn could cause strain the in the organization through long product cycles or definitely quality problems due to the lack of the understanding of the processes in the adjacencies that are needed. To start the discussion, Fig. 4.1 shows the materials engineer's role and the adjacencies as a hub and spoke network. This type of network is needed to start thinking of materials or other competency domain from a system point of view which will help enhance the product design cycle and reduce inefficiencies. The lack of training of the materials engineer in the areas of design, Product verification and Validation, Manufacturing and assembly, and supply chain, make such a

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https://doi.org/10.1007/978-981-15-1263-6_4

Fig. 4.1 Materials engineering Hub and spoke, Author Chart

person reduced to add value in the beginning of the design cycle and ineffective to the organization for the rest of that product cycle until an undesirable event occurs where their expertise in failure analysis are needed. However, had that person was involved throughout the design process many of the issues faced later would have been mitigated. Such a process already exist in many organizations, however, the execution is always lacking. Moreover, having veterans in organization with interdisciplinary skills is rare and such talent needs to be bred to lift the knowledge of the organization.

The engineering community in the past tended to be systematic and the engineer was a mathematician and philosopher. Today, the needle has shifted to either a single domain person with a hard time to communicate or generalist who cannot solve any deep problems. The approach of Adjacencies will help drive an enterprise toward a more complete engineering staff and reduce product improvement program due to a system approach in dealing with the product cycle from the inset. The type of engineer being discussed will be evaluated and their career development will be based on the following scale as shown in Fig. 4.2.

The scale in Fig. 4.2 reflects the current status of expertise a person has where 6 designate an expert as shown by the yellow curve while the green curve identifies the gaps and state of expertise. It should be noted that a person need not attain a high expertise level in the adjacencies but rather be proficient to collaborate with

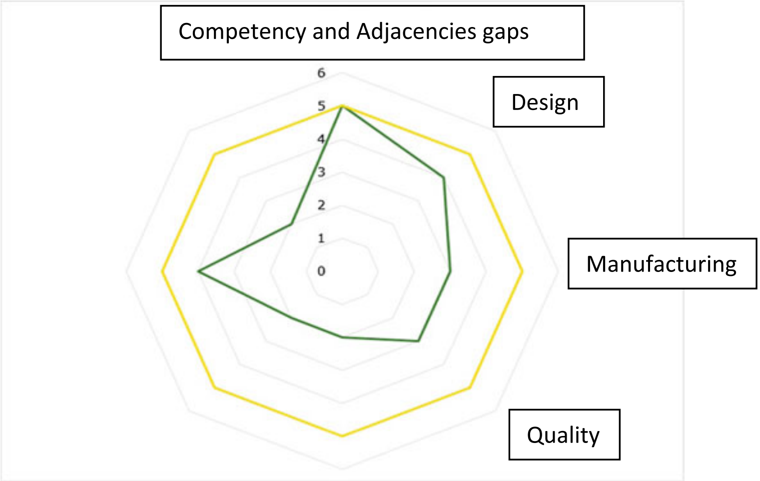


Fig. 4.2 Expert scale gaps in adjacencies, Author Charts

the experts. Now, how does this relate to light weighting and how can it be applied across an enterprise will be discussed next.

4.2 Discussion

The need to break the paradigm that an enterprise is stuck in requires system skills in product design and understanding of roles. A materials engineer does not have to be a designer but rather needs to understand the effect of materials selection on the design and manufacturing processes. Also, it should be understood by a materials engineers the influence of the materials and manufacturing processes on the virtual and experimental verification on the product. Moreover, the type of defects and production issues need to be identified and dealt with a priori. Many of these skills are taught at many universities and many enterprises have their own training programs to bring employees to a contributing member of the organization. In my experience, I found out that many engineers forget the basics once they join the workforce. I find people lack the knowledge of how to calculate the moment of Inertia of a section or that heat treating a component does not change its elastic modulus. Similarly, universities have lost the expertise in teaching basic manufacturing skills as machining, stamping, forging, or welding and never mind adhesive bonding. I have visited many Universities that will spend hours and hours preaching nano and bio materials and their students are clueless about a simple bolted joint calculations. Please don't misunderstand, I am for Nano and Bio but for enterprises to make products the basics should be understood, hence my motto "Learn The Basics, then Innovate". The same could be said for the rest of the competencies and the Universities, where I was on the advisory board of a Mechanical engineering department and the students do not learn CAD, FEA, or CFD, which are considered the skills for the new enterprises.

This type of outlook on Competencies, design, manufacturing, and the environment will optimize the product design and reduce inefficiencies in the system and will also drive a culture of quality where it will become a byproduct and not a competency. An example of deploying Aluminum in an enterprise will be discussed from a system view as shown in Fig. 4.3.

As seen in the figure above, it is not enough to decide to lightweight products, it is imperative to build and prepare the infrastructure for that. To decide to deploy Aluminum requires, the knowledge of the material, the manufacturing processes, the design guidelines, tools available for optimization, etc. Such an infrastructure, requires many years of investment in R&D and personnel to deploy when the time is right. Many organization follow the copycat model, where the competition introduces a product and the approach is me too, before they have the proper skills.

An example of designing a beam from Aluminum to lightweight a steel replacement, requires to make up a stiffness from the material side by a factor of 3. This

Fig. 4.3 Aluminum adjacencies for an enterprise, Author Chart

is exactly where design comes into use the geometry of the structure to yield the desired rigidity. Hence, the approach is always to use the Materials properties, the design, and the customer usage to yield the desired function is shown in Fig. 4.4.

Such a process, helps the engineers keep track of all aspects of the product design process and ensures that the system is well taken care of. Back to the example from above, the equation needed to ensure the equivalent design requirement is simply a freshman level type of an equation where the Material and Geometric stiffness is balanced at both sides of the equation as shown in Fig. 4.5.

As to the manufacturing process for the Aluminum section, it is obvious that an extrusion process will yield the desired shape at the lowest tooling cost. This balance between Materials, Design, and Loads from the duty cycle is a key in any product design and should be followed no matter what the product is. It has been shown over and over that anytime one of the elements of the process are violated that the design is

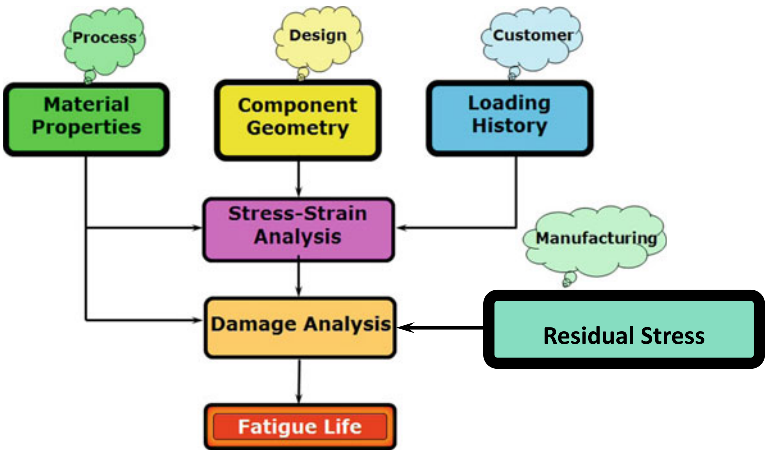
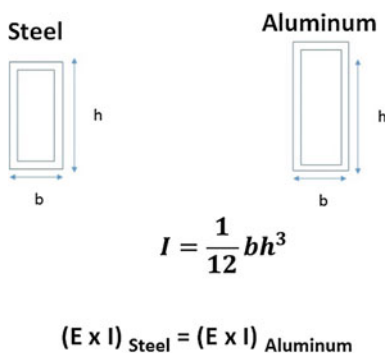


Fig. 4.4 Analysis process, Internal Handbook Chart

Fig. 4.5 Functional rigidity balance



doomed to suffer from quality issues that will keep recurring throughout the product lifecycle.

As was shown above, it is a rudimentary mathematics that the rigidity of the structure is preserved by doing these calculations. The rigidity is at least the same and the mass is lower, hence, the frequency response has been pushed up. It is this type of simple rules of thumb, without FEA, that can help the materials engineer add value in introducing new materials for a customer solution in the enterprise. It is not enough to say Aluminum has 1/3 of the elastic modulus of steel so we need to beef up the section or AHSS has a 700–1500 MPa strength so we can reduce the section from 3 to 2 mm. Such a general statements can be detrimental to design and can also give these advanced materials a bad taste, since the function of the product will not meet the customer expectations.

Consider another example to lightweight a steel casting to Aluminum one. The process follows as in Fig. 4.5 with a slight modification to the design, where a topology optimization is needed to substitute for the equation. Figure 4.6 (http://www.altairatc.com/(S(rfs4o2whprtbiaaazxof4unk))/europe/Presentations_2009/Session_05/SWEREA_Topology%20Optimization%20of%20Castings_091103.pdf) shows an example of such a change in design and topology to yield the desired function.

This type of system approach where the design, manufacturing process, optimization and cost structures are considered upfront is really common sense but not practiced regularly in the industry. The problem lies in the education and culture. The educational institutions are becoming silos of information where the theory and virtual tools are not connected and practiced. Moreover, the lack of programs in manufacturing engineering, assembly, and virtual processes simulation is resulting in engineers who design without knowledge of manufacturing processes or materials knowledge. In the US you would really have a hard time hiring a person with machining competency and the same can be said for all the other manufacturing processes. Once you find such a person, his skills in Manufacturing Simulation tools are zero. So when a design is given to him, his understanding of available simulation tools

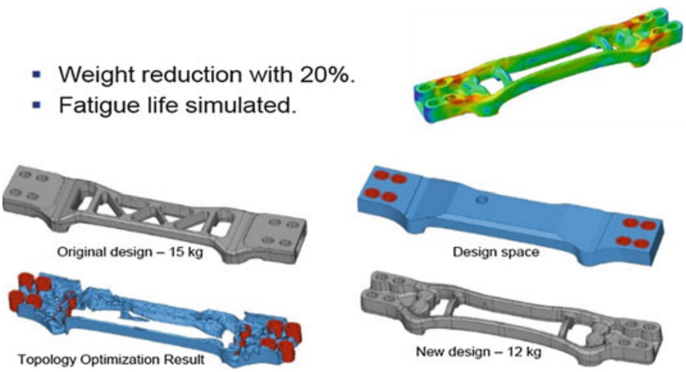


Fig. 4.6 Topology optimization

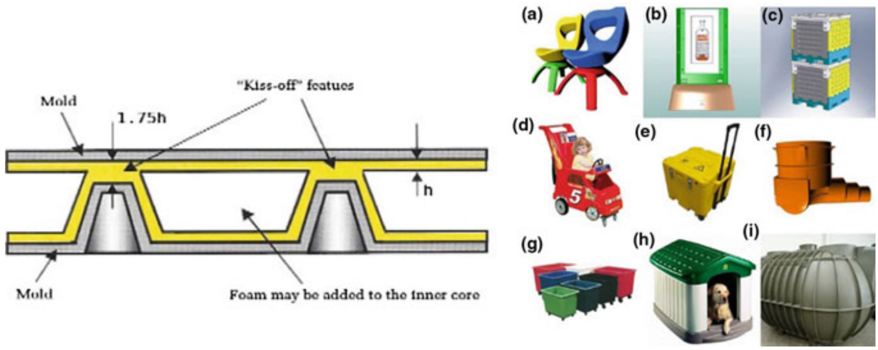


Fig. 4.7 Typical rotomolded design and components

is not existent and time gets wasted in building fixtures and the process of trial and error becomes the dominant tool. Many of the manufacturing processes, welding, casting, stamping, forgings, etc. can be simulated just like structural analysis tools are.

The story is not different if we go to Polymers or composites. For example to design a rotomolded component, one needs to understand the process, the design guidelines, effect of the process and material on the shape and analysis, and the cost structure. Figure 4.7 shows a typical rotomolded component intended for a rigid structure (https://rotoworldmag.com/about-rotomolding/).

The use of the process to generate box section for making up for the lack of elastic modulus is becoming clearer. The rigidity of the section has to be made up through design and the section should be able to withstand the loads from the customers' usage.

The picture is becoming clearer as the design, process, analysis, experimental testing, supply chain, costing structure are thought of as a system and not as silos, the engineer can design a better reliable product at the optimized cost and meeting the customer's expectations.

4.3 Conclusion

A system approach to designing lightweight components was discussed and outlined. If we build a career with the knowledge needed to drive such an approach, a person would automatically progress through the ranks provided the soft skills are there. This was written because after years in the industry, the universities have not changed their approach and the industry is not seeing the importance of system thinking from this viewpoint.

Chapter 5
Light-Weighting in Transportation and Defence Using Aluminium Foam Sandwich Structures

J. Banhart, F. García-Moreno, K. Heim and H.-W. Seeliger

Abstract We review the status of Aluminium Foam Sandwich (AFS) technology and discuss both recent improvements of foaming technology and current applications. It is concluded that the quality of foams has improved in the past years and costs are slowly decreasing. This is why applications in which metal foams have more than one function are more likely to be economically viable. The examples presented here include battery cases for electric cars, crash absorbers, high-speed train front heads and blast protectors for vehicles and tanks.

Keywords Transportation · Defence · Light-weight structure · Aluminium foam · Sandwich panel

5.1 Introduction

Aluminium Foam Sandwich (AFS) is a product comprising a highly porous aluminium alloy foam core and two aluminium alloy face sheets. The layers are firmly attached to each other by metallic bonding. Use of such sandwich panels has been proposed for many industrial sectors including automotive (Degischer and Kriszt 2002; Banhart 2005), ship building (Banhart et al. 1998), railway and aircraft industry (Yu et al. 1998). Sandwich panels compared to dense material or bare foam have various advantages. They are stiffer than dense sheets of equal mass (Ashby et al. 2000). Compared to bare foam without face sheets the main advantage is that the outer skin allows the sandwich to bear tensile loads that occur, e.g. when the panel is bent. Bare metal foam alone performs poorly in tension and panels fracture quickly on the outer side. Aluminium foams reinforced with metal wires or meshes (Simančík et al. 2001, 2002) improve this situation similarly to AFS. They lead to better tensile properties but are less efficient in accommodating compressive stresses. In sandwich

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panels, the porous foam core is hidden inside a dense material which avoids possible problems with surface damage or corrosion. Provided the edges are sealed the aluminium foam can be completely inaccessible to liquids and gases. Compared to sandwich panels where face sheets are merely glued to a sheet of metal foam, the pure metallic character of AFS is an advantage whenever flammability, heat resistance, weldability, recyclability or long term stability are an argument. In the following, we shall briefly review the advances in manufacturing technology and describe a number of promising applications of AFS in transportation and defence.

5.2 Manufacture of Aluminium Foam Sandwich Panels

Manufacture of AFS is based on the expansion of metallic precursors driven by the decomposition of an embedded blowing agent ('P/M process') (Allen et al. 1963). Such precursors allow for filling complex moulds and producing shaped parts of all kinds. They can also be used to bare foam plates provided that suitable moulds are available. If sandwich panels are required, metallic face sheets can be bonded to such plates.

The AFS technique is mould-free and does not require any bonding step. Here, a three-layer composite comprising a central foamable layer made of consolidated metal powder/blowing agent mixtures and two solid face sheets is used, see Fig. 5.1. Upon heating to a temperature high enough to foam the lower-melting core layer but low enough to prevent the higher-melting face sheets from liquefying, the composite expands to an AFS panel (Baumeister et al. 1994). Bonding between core and face sheets is metallic both before and after foaming. To ensure flatness of the resulting AFS, a hot calibration step after foaming is recommended. All manufacturing steps on an industrial scale are shown for better understanding in Fig. 5.2: Powder filled ingots, rolling process, rolled three-layer composite precursor, foaming furnace.

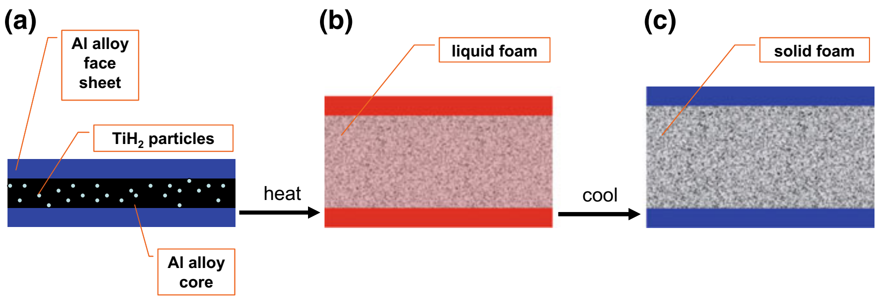

Fig. 5.1 Principle of AFS manufacture. **a** Three-layer composite with a central core layer made of a compacted mixture of metal powders and blowing agent powder, mostly thermally modified TiH_2. **b** Composite expanded upon heating. Only the core changes its volume, whereas the face sheets remain unchanged. **c** Fully expanded and solidified AFS after cooling

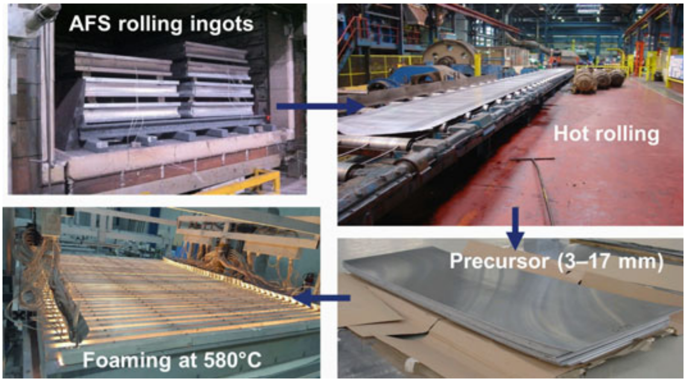

Fig. 5.2 Images taken from various stages of AFS precursor manufacture. Upper left: Powder-filled ingots read for rolling, right: rolling process, lower right: rolled three-layer composites after rolling and cutting, lower left: foaming furnace

The advantages of such an integrated process include the absence of any non-metallic bonding, the intrinsic non-flammability and the option to create 3D-shaped parts by pre-forming the three-layer composite prior to foaming or by hot calibrating the AFS after foaming (Banhart and Seeliger 2008). Disadvantages include the restricted set of possible alloy combinations for the core and face sheet due to the necessity to coordinate the melting temperatures of the core and the face sheets, the need to use expensive metal powders and the high number of processing steps. Possible ways to overcome the problem have been discussed (Banhart and Seeliger 2008), but up to now no viable solution has been demonstrated.

The alloy combinations that have been in use for both core and face sheets until a few years ago are listed in Table 3 of Banhart and Seeliger (2008). In most cases, the alloy AlSi6Cu4 or AlSi6Cu6 was used for the expandable core, since this alloy starts to melt at 524 °C, which is low compared to the melting point of the face sheet materials applied (different commercial 1000, 3000, 5000 and 6000 series alloys). However, copper is heavy, expensive and causes corrosion. Therefore, replacement was sought and found in the system Al-Mg-Si (Helwig et al. 2011). Among various suitable alloys the alloy AlSi8Mg4 (±1 wt% for Mg and Si) is one with outstanding foaming behaviour (good expansion, small and regular pores) (Helwig et al. 2011) and is in general use now. Another advantage of replacing Cu by Mg is the improved corrosion resistance (Fig. 5.3).

A key point for the improvement of foam quality in recent years has not only been the choice of a new alloy but also a very precise conditioning of all metal powders used. Contaminations, especially by atmospheric moisture or dust have to be avoided since those were found to have adverse effects on the uniformity of pore size distributions of foams made from such starting materials. The explanation for such effects is that the bonding of individual powder particles during compaction is compromised by chemical adsorbates or impurities at the powder surfaces, which then leads to

Fig. 5.3 $1 \times 1\ m^2$ large AFS sliced in the panel plane

weak points in the structure. When the gas evolving from the blowing agent (hydrogen when TiH_2 is used) inflates the bubbles and expands a powder compact during foaming, large pores can be formed at such weak points. Such pores can be larger than the thickness of an AFS under unfavourable conditions, have an adverse effect on mechanical properties and also give rise to an undesirable appearance, see Fig. 5.4 (top). In contrast, AFS panels exhibiting a favourable pore structure expressed by a predominant pore size in the range of 1–1.5 mm and only few larger pores are obtained after tuning the process parameters accordingly, Fig. 5.4 (bottom).

Another key point is the foaming process. A fully controlled and automated array of infrared heating lamps was found essential for foaming large panels. Temperature gradients above ~15 K across the entire surface lead to premature foaming (e.g. in the middle) and corresponding damage of the pore structure by propagating cracks and/or an undesired variations of pore size.

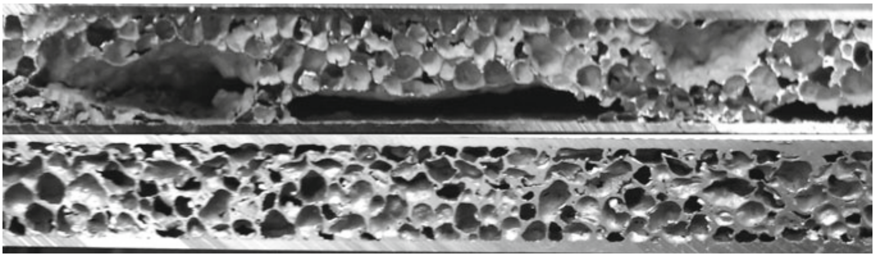

Fig. 5.4 (Top) AFS made without carefully adjusting the powder and processing parameters and exhibiting individual large pores. (Bottom) AFS made by applying the current knowledge concerning especially powder degassing. Thickness of panels is ~10 mm

Table 5.1 Basic data of commercial AFS material (taken from Pohltec Metalfoam GmbH 2017)

Parameter	Range
AFS sheet size	Max. 2500 × 1100 mm
Total thickness	9–80 mm
Face sheet thickness	0.65–10 mm
Flatness of AFS	1 mm/1000 mm
AFS thickness tolerance	±0.5 mm
Cover sheet alloys in use	3103, 5005, 5754, 6082
Core alloys	AlSi6Mg3, AlSi8Mg4, AlSi6Cu6

5.3 Products

AFS can be intrinsically large and much effort has been put into up-scaling of both precursor manufacture and foaming equipment. The maximum size currently achievable is 2500 × 1100 mm^2 (Pohltec Metalfoam GmbH 2017). This is not a fundamental limit but given by restrictions in producing three-layer composites with 1100 mm width—restricted mainly by the rolling step—and the difficulty in heating a large panel up from room temperature to the foaming temperature around 600 °C while keeping the temperature everywhere within a certain margin. Figure 5.3 shows a large panel of AFS than has been cut open along the central plane and demonstrates the absence of abnormally large pores and other defects over this large area.

The annual production rate of one such foaming furnace is currently 9000 m^2, extendable to 20,000 m^2 by introducing production around the clock. Some basic data of such materials are summarised in Table 5.1. Costs have been slightly decreasing in the past few years. How much a given AFS panel costs depends on the exact foam/face sheet configuration and the production volume.

5.4 Principles of AFS Application

Light-weighting involves reducing the mass of a component while keeping its mechanical properties at the required level. The property in question is often stiffness but other properties can also be a target for optimisation. There are three groups of properties which are favourable in metallic foams (Banhart 2005):

- Elastic properties: Young's (E) and other moduli (e.g. G) of metal foams usually scale with $(\rho^*)^2$, where ρ^* is the apparent density of a foam,
- Plastic properties: foams collapse at a nearly constant stress and the associated collapse strength σ_c also scales with a power of ρ^*,
- Functional properties of metal foams involve thermal and electrical transport coefficients, electromagnetic or acoustic damping etc. Some of them are directly related to ρ^* but also might depend on cell morphology in a complex way.

Table 5.2 Stiffness optimisation of a $1 \times 2\ m^2$-large panel. The reference point is a steel sheet of a given stiffness which is replaced by aluminium, CFRP and AFS (face sheet material = alloy 6082)

	Steel	Aluminium	CFRP	AFS
Required thickness for equal stiffness [mm]	4.7	6.8	5.6	8.0
Mass [kg]	73.3	36.6	17.0	12.8
Mass reduction [kg (%)]		−36.7 (50%)	−56.3 (77%)	−60.5 (83%)
Cost [€ (₹)]	73 (5500)	109 (8200)	510 (38000)	128 (9600)
Cost/1 kg mass reduction w.r.t steel [€ (₹)]		1 (75)	7.7 (580)	0.9 (68)

The bending stiffness S of a slab of foam scales with h^3, where h is its height, and the apparent young's modulus E^*. Consider foaming a dense precursor sheet that can be foamed in the thickness direction by heating. The mass of this sheet is nearly constant as gas is released from the blowing agent, bubbles are formed and the height of the foam increases. As $E \propto \rho^2$ and $\rho \propto h^{-1}$, stiffness increases linearly with h: $S \propto h$. Thus foaming at a constant mass increases stiffness and metal foams are stiffer than metal sheets of the same mass. Table 5.2 compares such a stiffness optimisation using a steel sheet of a certain size and mass as a reference point and replacing it by different materials including AFS. Clearly, AFS offers the highest potential for mass reduction.

The optimisation process is a lot more complicated when other properties are involved. For example, the plastic deformation behaviour can be an important issue as well as other functional properties and no simple comparisons such as in Table 5.2 can be given.

Beside material's properties of AFS technological or economical properties can limit or favour application. For example, the fact that AFS can be machined, cut or welded similar to conventional aluminium material facilitates application.

5.5 Application Examples

5.5.1 Battery Case for Electric Cars

In traditional combustion engine driven cars, the body-in-white (BIW) has been in general the same for decades and has been developed mainly under the viewpoint of the use of aluminium alloys or steels. The integration of AFS or even any other metal foam into this highly optimised system is therefore very difficult. AFS provides an excellent weight-saving potential of up to 70% while keeping the bending stiffness constant. However, it is a novel and complex material just by its dimensions: the thinnest AFS consists of 6.5 mm foam and two 0.75-mm thick face sheets (8 mm

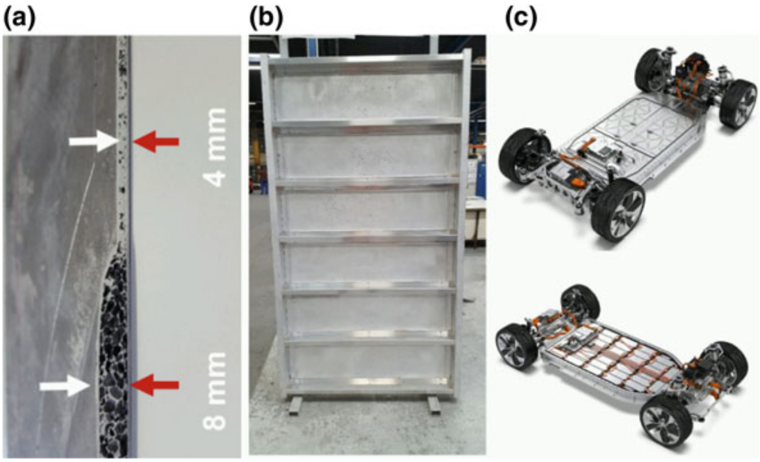

Fig. 5.5 Concept of underbody and battery compartments of an electric vehicle. **a** Compressed AFS panel used to obtain sealed edges, **b** module comprising underbody (reverse side) and battery compartments (obverse), **c** location of prototype in electric car (Jaguar I-pace concept car)

total thickness). Hitherto, in standard BIWs, metal sheets of 1–3 mm thickness have usually been employed. Therefore, a direct substitution of traditional sheet-based structures by AFS would lead to an overdesign and be economically not reasonable.

For electric cars, the design is still not clear and various conceptual lightweight construction solutions are possible. The absence of a large engine in the front (or back) of the vehicle and the necessity to transmit power to the wheels from there allows for a flat underbody construction—which is the first criterion facilitating a reasonable use of AFS. Electric engines can then be placed on the axes directly. On the other hand, the batteries represent a large fraction of the mass of the vehicle and require a lot of space and have to be accommodated. One simple but very promising design, which might establish a standard for most electric cars, is shown in Fig. 5.5b, c. In this "skateboard" design, the batteries occupy the space between the underbody sheet, the passenger compartment floor and the wheels. In this way, the centre of gravity is kept low, thus improving the dynamics of driving. The two sheets (underbody and passenger compartment floor) can be separated by vertical struts and in this way stiffness is improved. The traditional design used for most of the battery compartment modules consists of a multilayer structure of various Al or steel plates fulfilling various requirements (e.g. impact protection, cooling, bracing, etc.). While this is a viable solution, it adds considerable mass to the car. Along the principles outlined in the previous section an alternative solution based on AFS was designed. The AFS concept battery compartment consists of an underfloor (final layer to the street) and floor panel (border to the passenger cabin). Both were made of AFS and were bonded to extruded aluminium alloy profiles by punch rivets and automotive adhesive, see Fig. 5.5b. Partial densification of some AFS areas, see Fig. 5.5a, was carried out to seal the elements and to connect them to the substructure by using standard connection techniques (riveting, glueing, etc.). However, the largest part of the AFS was not densified. This procedure led to an increased stiffness and impact protection, while mass was reduced. Thus, the mass-specific properties were improved. Figure 5.5c shows how the battery compartment integrates into a Jaguar I-pace concept car.

Further essential aspects that make AFS appear a suitable replacement for steel or aluminium alloy sheets are improved structural and functional properties besides stiffness, namely:

- Higher damping of electromagnetic radiation (EMC compatibility),
- More safety in the case of a battery failure,
- Protection of the battery from external impacts, especially from puncture by sharp objects,
- Improved sound and vibration damping,
- Additional crashworthiness.

Moreover, the fact that the material can be used in the assembly process of a vehicle in a very similar way as bulk aluminium applying standardised and proven production techniques is an additional advantage.

5.5.2 Crash Absorbers

New trends and developments in the automotive industry, especially in the electric car segment, increase the demand for new concepts and materials for lightweight construction. Furthermore, new car designs are necessary due to the rearrangement of components, making it possible to consider cellular materials from the beginning. Passenger safety is another important factor, where a light, as compact as possible but very effective crash protection system is needed especially because the available crash space is reduced due to the absence of the traditional front engine. An example is shown in Fig. 5.6. Metal foam parts developed by the Technical University Berlin and Pohltec Metalfoam are foreseen in the prototype of an ultra-light electric vehicle recently developed in the European project ‘Evolution’ by a number of companies including Cidaut (Valladolid, Spain), Pininfarina (Cambiano, Italy) and Pohltec metal foam (Cologne, Germany).

5.5.3 High-Speed Trains

Railway industry is an important factor in future mobility concepts. Promising prototypes have evolved in the past years as possible future serial application.

AFS foam panels delivered by the IWU (Chemnitz, Germany) have been used in the floor of a wagon of the metro in Peking in continuous operation without issues since 2008. Among their advantages shared with other applications, the property of

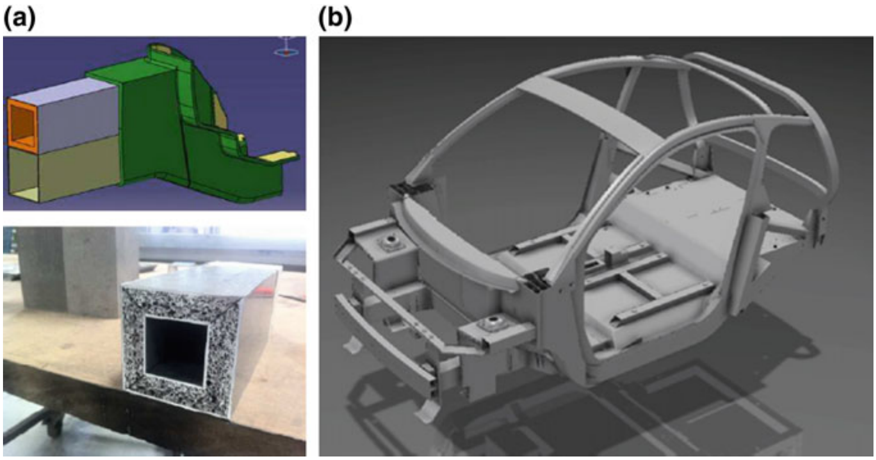

Fig. 5.6 **a** Crash absorber box of the electric car prototype developed in the European project 'Evolution'. It is made of rectangular aluminium alloy profiles filled with Al-foam. **b** CAD design of the body in white (Garcia-Moreno 2016)

being not hygroscopic and the acoustic properties that are similar to those of wood have been named (Hipke 2016).

A train front structure was welded from curved AFS plates by the Wilhelm Schmidt GmbH (Groß-Kienitz, Germany) in cooperation with the Brandenburgische Technische Universität Cottbus (BTU, Cottbus, Germany) (Sviridov et al. 2012; Viehweger and Sviridov 2007). A more prominent and recent prototype is the power head cover of the Intercity-Express-Train (ICE) train fabricated by Voith Engineering (Ludwigsfelde, Germany) and IWU (Chemnitz, Germany). It is made of welded AFS plates and carbon fibers in the front, with a total length of around 6 m (Fig. 5.7). A mass

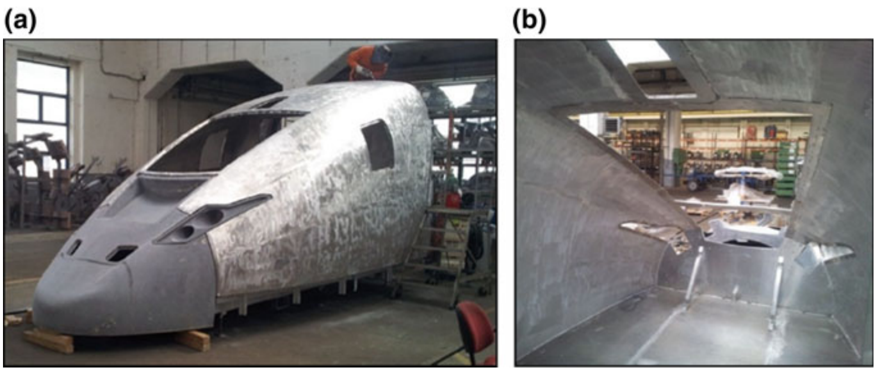

Fig. 5.7 **a** Prototype of German high velocity train ICE made of welded aluminium foam sandwich. **b** View of the interior demonstrating the low number of components required (courtesy of Thomas Hipke, IWU, Chemnitz, Germany and Voith Engineering, Chemnitz, Germany)

reduction of 18% was achieved while maintaining stiffness at the same level, thus improving vibration damping and additionally reducing the number of manufacturing steps compared to the traditional construction procedure. These examples clearly show the advantages of metallic foams or AFS panels against honey comb panels, especially when curved sections are required.

5.5.4 Protection Against Blasts, Bullets and Other Hazards

Protection against bullets and explosions requires special material combinations. A combination of AFS with a stone plate has proved to be efficient to stop bullets fired from NATO and Kalashnikov guns. The hard stone front plate fragments the bullet and the following aluminium sheets and foam on the back stop the fragments and dissipate energy, see Fig. 5.8a, b.

Use of metal foam for armour has been suggested before for various configurations (Gama et al. 2001) but the combination stone/AFS is especially attractive for architecture: The AFS sheet is a convenient light carrier material and allows for fixing the structure. The stone is the material that can be displayed. The anticipated use is on or in buildings such as banks or in public building under threat. As there is little ageing and corrosion in AFS structures, outdoor use is possible without any problems.

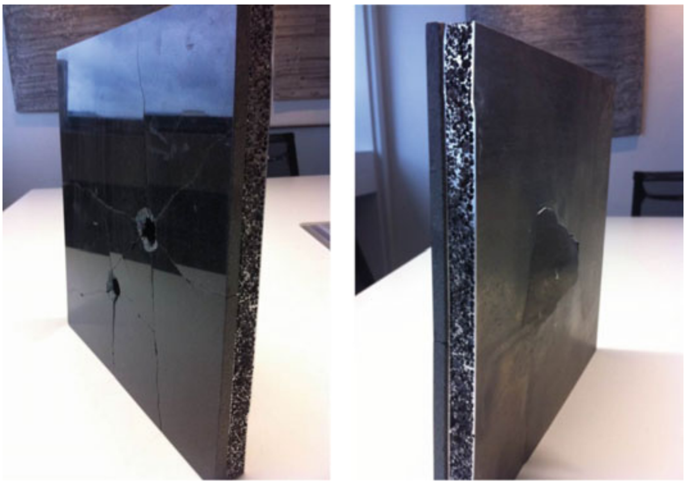

Fig. 5.8 Composite of an AFS panel with a polished granite front plate hit by a bullet. The AFS had 1.8 mm face sheets and a 20 mm foam core, while the granite plate was 8 mm thick

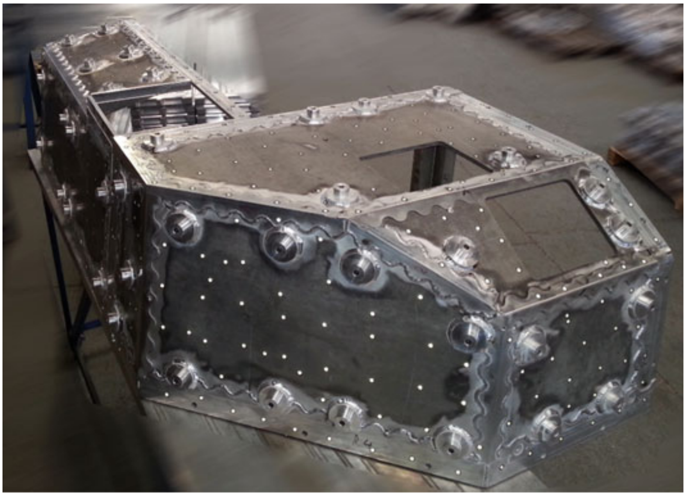

Fig. 5.9 Ammunition hood of a reconnaissance tank

5.5.5 Ammunition Hoods for Armoured Reconnaissance Tanks

AFS has found application in military vehicles. Selected reconnaissance tanks have been equipped with ammunition hoods to reduce their mass. The background for this was the requirement to reduce mass to a level that various such tanks can be transported in aeroplanes at a time. Such an ammunition hood is shown in Fig. 5.9. AFS is used in the wall areas and serves as first safety unit and a carrier for a bullet-proof Kevlar plate, see cylindrical attachments on AFS panels in Fig. 5.9. In this way, the total mass could be reduced by 80 kg, which in turn leads to a more efficient use of the transport capacity of the military aeroplane.

5.6 Outlook

Aluminium foam and here especially aluminium foam sandwich (AFS) technology has led to a number of promising small-scale applications. What is important for the development of the market is the availability of materials in quantities of tens of thousands of m^2 annually. Experience has shown that without a reliable source of material the search for applications in companies is slow which, in turn, slows down the development of manufacturing technologies. This is the well-known ‘chicken and egg problem’ of new materials.

The past years have seen an improvement of foam quality. Pore size distributions are now more uniform and large pores can be avoided. The cost of the product has been reduced slightly in the past. Strategies to bring costs further down include combining various process steps into fewer integrated steps, e.g. to combine powder consolidation and rolling as suggested in Banhart and Seeliger (2008). Such integrated technologies have been found to be difficult to control and sometimes have a negative impact on foam quality but still they are the right way to go. Lightweighting in the transport and military sector is a challenging but also rewarding area of application for aluminium foam sandwich panels.

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Chapter 6
Innovations in Materials and Engineering for Light-Weighting Aircraft

Success Story of India's Advanced Light Helicopter and Light Combat Aircraft

C. G. Krishnadas Nair

Abstract Climate change summit held in Paris 2015 reaffirmed the responsibility of the nations to reduce burning of fossil fuels to arrest global warming. Aviation worldwide accounts for 3% greenhouse gas emission and being at higher altitude it is 3 times more damaging to the ozone layer. Light Weighting of Aircraft is very important to reduce the fuel consumption leading to reducing pollution. In addition, it improves fuel economy and performance. Aircraft designers use materials with higher specific strength, specific modulus and fatigue strength and such other properties to design aircraft structures with lower weight. Innovative design using innovations in engineered materials such as composites, metal honeycomb sandwich structures and manufacturing processes such as co-cure and co-bonding to reduce the number of subassemblies, reducing the number of fasteners lead to weight reduction. Innovations in miniaturization of aircraft equipments using MEMS technology, reducing weight of electric harness using innovations in materials to develop light weight cables and even reducing the weight of paints using new technologies help in reducing weight. The paper gives a step by step approach to light weighting of aircraft on the above basis. This is illustrated through case studies of India's advanced light helicopter and light combat aircraft.

6.1 Introduction

Breaking of the one trillion ton Antarctic iceberg on 12th July 2017 is the recent of a series of warmings over the years to humans by 'mother earth' of the danger of global warming caused by humans. Global warming is directly related to the increasing emissions of CO/CO_2, NO_x and burning of fossil fuels represent the largest share of emissions (Fig. 6.1), Air, ground, inland water and marine transport vehicles account

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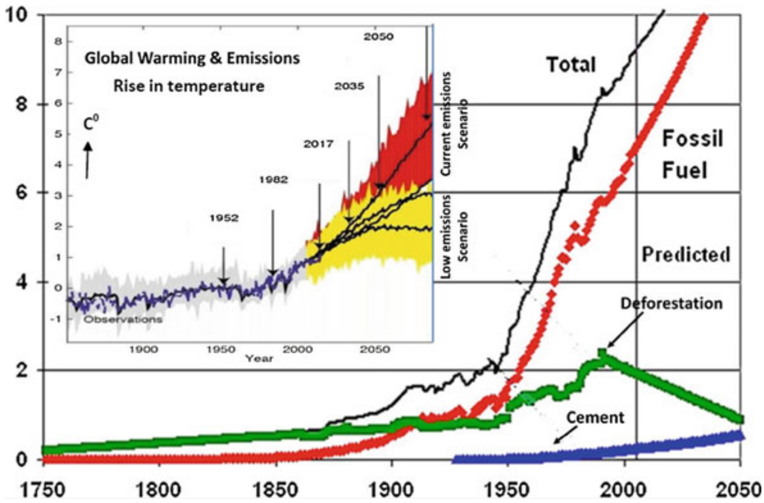

Fig. 6.1 CO_2 emissions in billions metric tons per year and global warming

for the 'lion's share' in this. During the Earth Summit in Rio De Janeiro in 1992, global leaders from 172 countries formally recognized the threat of green-house gas emissions and planned to bring it down. Kyoto Protocol in 1947 made the nations to take quantified responsibilities. The climate change summit held in Paris (2015) attended by 190 countries reaffirmed the responsibility to take positive action by reducing the use of fossil fuels. Light weighting of transport vehicles is a 'must' to achieve this.

It is estimated that aviation-worldwide accounts for about 3% of the greenhouse gas emissions -CO_2/CO, NO_x and carbon suit. Unlike the emissions from ground and marine transport, emissions from aircraft, being at higher altitude, are more damaging to the ozone layer and contribute to the global warming by a multiplication factor of three. Figure 6.2 shows fuel consumption as a function of the gross weight of a large aircraft at a constant speed and illustrate the advantages of light weighting the aircraft (Anderson and Eberhardt 2007). Reduction of weight will lead to reduction of fuel consumption and reduce pollution and also improves the fuel economy leading to cost effective and profitable operation (and better flight performance especially for military aircraft).

The process of weight reduction involves use of lighter and stronger materials, with higher strength to weight ratio (specific strength and specific modulus) along with considerations of enhanced properties such as fracture toughness, fatigue strength, resistance to crack propagation, corrosion resistance and stress corrosion resistance etc. Another method is using engineered materials such as fibre and particulate reinforced composites and light weight highly rigid sandwich structures. Innovative design using innovations in manufacturing is another approach to weight reduction. One example is Integral milling of pockets, making cut outs and lightening holes, local thinning by chemical milling etc. without compromising structural

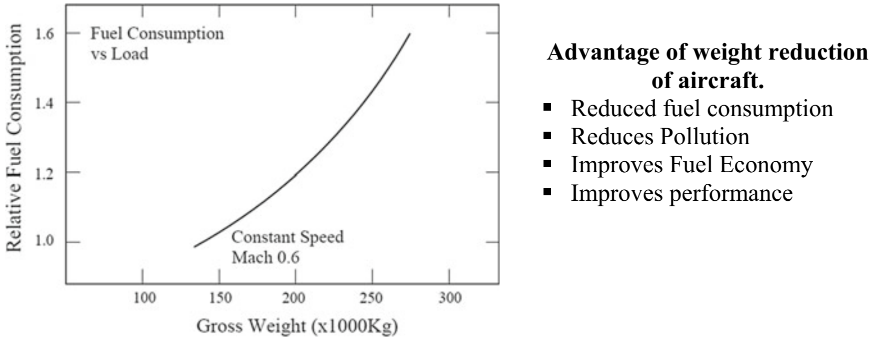

Fig. 6.2 Fuel consumption as a function of gross weight of Aircraft (Anderson and Eberhardt 2007). Adopted from original plot in reference (1) based on data provided from large airplane manufacturers

integrity. Another is innovative design to reduce the number of sub-assemblies and thus number of riveted joints leading to reduction of number of fasteners for assembly. This is achieved by design and manufacture of bonded structures, co-cure co-bonded composites, 3D printed and Single moulded large structures.

Figures 6.3 and 6.4 illustrate specific strength and specific modulus for various aircraft materials over a range of operating temperatures (Krishnadas Nair 2006). Metallurgical and materials engineers are aware of designing with materials with higher specific strength and specific modulus to produce lighter weight components and structures.

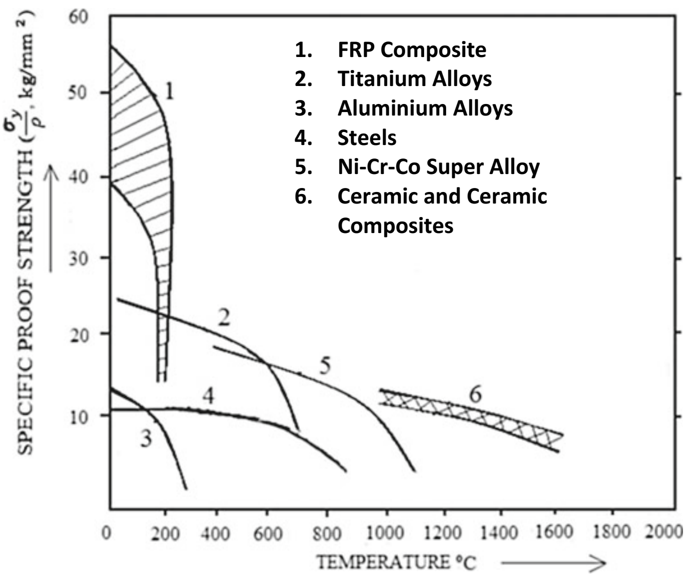

Fig. 6.3 Specific proof strength versus temperature for aircraft materials

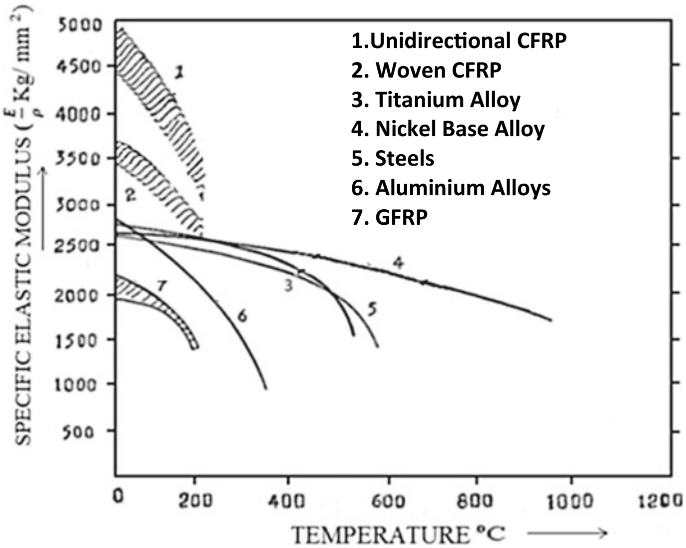

Fig. 6.4 Specific modulus versus temperature for aircraft materials

Designers use materials of higher specific strength and higher specific modulus to design structures to keep the structural weight as low as possible. Consider a simple case where the designer designs a structure primarily on the basis of strength to weight ratio and so on the basis of specific proof strength S′ (ratio of 0.2% proof strength to density of material). Weight of structures of two materials (1) and (2) is a function of its specific strength S′ of each

$$w_1 = fs_1^{'}$$

$$w_2 = fs_2^{'}$$

For condition $s_2^{'} > s_1^{'}$ w_2 will be less than W_1

The weight reduction ($W_1 - W_2$) as a percent of W_1 is covered by the equation:

$$\frac{(w_1 - w_2) \times 100}{w_1}\% = \left(1 - \frac{s_1^{'}}{s_2^{'}}\right) * 100\%$$

For a structure for e.g. abeam, subjected to bending loads the rigidity measured in terms of deflection (Δ) of the beam is inversely proportional to the specific modulus $\frac{E}{\delta} = E'$ where E is the modulus of elasticity and δ is the density of the material.

Deflection $\Delta = \frac{PL^3}{3EI}$ where P is bending load, L—length, b—width and t—depth of the beam, I is the moment of inertia.

$$I = \frac{bt^3}{12}$$

$$\Delta = \frac{PL^3}{3EI} = \frac{12PL^3}{3Ebt^3} = \frac{4PL^3}{Ebt^3}$$

Thus deflection Δ and therefore the rigidity of the beam is inversely propositional to modulus of elasticity E of the material and inversely propositional to the cube of the depth of the beam. For condition $E_1^{'} > E_2^{'}$ for materials (1) and (2) W_2 will be less than W_1 for constant Δ.

$$\frac{W_1}{W_2} = f\frac{1}{E_1^!}\Big/\frac{1}{E_2^!} = f\frac{E_2^{'}}{E_1^{'}}$$

Weight reduction, $\frac{W_1 - W_2}{W_1} = \left(w_1 - \frac{W_1 E_1^{'}}{E_2^!}\right)\Big/ W_1 = \left(1 - \frac{E_1^{'}}{E_2^{'}}\right) * 100\%.$

The above analysis is a very simplistic approach. In actual practice the structures are subjected to tensile, bending, fatigue, buckling and such other leads. A helicopter blade, supported at the rotor head is a cantilever subjected to bending loads, and centrifugal tensile stress on account of rotation of the blades. These loads vary in flight based on flight conditions and is also subjected to vibrational loads and hence must be designed for fatigue strength. An aircraft wing is subjected to tensile stress on the top skin and compressive stress on bottom skin while on ground and just the reverse in flight, and hence the designer has to consider tensile, bending and fatigue loads. Landing gear components are subjected to compressive loads while on ground and while taxying, and shock/impact loads during landing. The type of structures such as riveted, bonded, integrally milled etc. need analysis of stress concentration, residual stresses, rate of crack propagation and the like. Thus weight reduction (optimization) is a complex exercise for the designer considering several materials properties, safe guarding safety and structural integrity. Another fact to be considered is the cost of materials and the cost of process. Designers have to resort to IT tools and techniques and IT software based analysis for the same (Unigraphics; Cervellera 2007; Reducing Weight in Composite Aerostructures 2013; Kaufman 2008; Ahamed et al. 2014).

6.2 Different Materials and Strategies for Weight Reduction

Magnesium alloys form the lightest among aircraft materials and are potential weight savers for aircraft up to about 150 °C particularly as castings, with strength to weight ratio superior to aluminium alloy castings. Recent research and development on magnesium alloy composites using nano particles has shown the potential for enhancing usage of such materials in aircraft structures in the future with the advantage of weight reduction. Aluminium alloys form the single largest among aircraft materials due to their excellent all round properties such as low density, relatively high strength to density and high modulus to density ratios, fatigue strength, fracture toughness and corrosion resistance, ease of forming and low cost. Significant weight saving should consider developing newer higher strength and lighter aluminium alloys. Traditional duralumin type alloy (2014) is getting replaced by higher strength Al-Cu-Mg alloys 2017 and 2024 types and higher strength and stress corrosion resistant Al-Zn Mg-Cu-Zr alloys such as 7010 and 7050 and with 7085 alloys in the form of plates and forgings. Aluminium lithium alloys of lower density and higher strength such as 8090, 2090 and 2099 have also been developed and utilized to achieve weight reduction of airframes. Aluminium alloy foam and honeycomb light weight core materials and development of sandwich structures, as well as aluminium alloy—FRP laminated sheet fuselage skin materials have been used for aircraft. Further R&D leading to aluminium alloy matrix and nano particles based MMCs have potential for future applications, particularly for cast and 3D printed aircraft parts. Titanium alloys have excellent strength and resistance to oxidation up to 500–550 °C and offer as the best material for light weighting of aircraft structures in the range of 200–550 °C. Considerable weight saving is achieved by using titanium alloys by substituting steels for fasteners, under carriage and structural forgings and fittings. Low alloy steels, used for parts requiring very high strength such as high strength bolts, landing gear, wing attachments and such other structural fittings, gears and shafts can be replaced with higher strength micro alloyed light alloy steels to reduce weight.

While metallurgical engineers are familiar with the development and application of alloys with higher specific strength and modulus, may not be so in the case of ‘engineered materials’ such as composites and bonded structures for weight reduction. Hence, I would like to discuss briefly the same, before taking up specific case studies on ALH and LCA. Glass fibre, carbon or Kevlar fibre reinforced plastics with high specific strength are useful to substitute steels and aluminium alloys for structures subjected to temperatures below 120–130 °C and reduce structural weight. These are engineered materials offering opportunity for the designer to make structures with desired properties in each direction, and even functionally gradient properties. Hybrid FRP using a combination of two or more types of fibers gives the designers a choice to design light weight structures with the desired combination of strength and rigidity. Another example is aluminium alloy thin sheet FRP laminated layered composites.

Metal and plastic foam and honeycomb core bonded sandwich panels for making rigid structures such as floor boards, and beams subjected to bending loads have significantly contributed to light weighting of aircraft. For a structure subjected to bending loads, and deflection (Δ) is to be minimized the designer will consider materials of higher specific modulus. As already shown earlier deflection of structure such as a board or floor beam of an aircraft/helicopter will be inversely proportional to the cube of the thickness (depth) of the beam, higher the depth of the beam, higher the rigidity proportional to the cube of the depth. Increasing the depth for increasing rigidity for a solid section will increase the weight substantially. However, the depth of beam can be increased by designing it as a sandwich structure with very light weight metal/plastic foams or honeycomb as core and bonded with structural adhesives to thin top and bottom skins of metal or FRP. The top and bottom skin takes the tensile/compressive stresses, which gradually reduces to zero at the neutral axis.

Figures 6.5 and 6.6 illustrate the same (A Comprehensive Guide to Hexcel Honeycomb Materials and Properties). In the example shown replacing a solid sheet/plate structure of thickness ‘t’ by a honeycomb sandwich core leads to enhancing the relative bending strength and rigidity several times. Conversely to get the same bending strength and rigidity of the structure as for sandwich construction, the thickness of the solid section will have to be doubled and therefore the weight of the solid structure will be two times higher.

Another potential area for light weighting of aircraft is reducing the number of parts.

An aircraft structure is an assembly of several component assemblies leading to sub-assemblies and then major assemblies as illustrated in Fig. 6.7. Boeing 787 uses 2.4 million fasteners, about 70% aluminium alloy rivets and 30% high strength steel and titanium alloy fasteners weighing about 12 tons per aircraft at an average weight of 5 g/fastener. A 20% reduction in fasteners required for assembly will reduce weight by 2.4 tons. This can be achieved by making structures by integrally milling from plates instead of riveted assemblies, rivet-less adhesively bonded metal and composite structures, co-cure and co-bonded composites, large single moulded composites by wet-layup, vacuum assisted resin transfer moulding, investment cast moulding for complex pipe assemblies, 3D printing etc.

Alloy Material	Honeycomb
Aluminium Alloy 2.8 gm/cc	0.03 to 0.13 gm/cc
Titanium Alloy 4.5 gm/cc	0.05 to 0.20 gm/cc
Stainless Steel 7.5 gm/cc	0.08 to 0.40 gm/cc

Fig. 6.5 Designing lightweight highly rigid bonded sandwich structures with honeycomb/metal foams (comparison of densities)

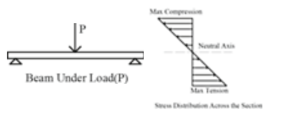	Solid Metal Sheet t	Sandwich Construction 0.5 t / 0.5 t, 2t
Relative Stiffness	100	740 7.4 times more rigid
Relative Bending Strength	100	380 3.8 times as strong
Relative Weight	100	103 3% increase in weight
Stiffness to Weight Ratio	1	7.18
Strength to Weight Ratio	1	3.69

Fig. 6.6 Comparison of relative stiffness and bending strength of solid metal and sandwich structure with an indexed value of 100 for solid metal Reference 8 concept adopted from and data used from publication of Hexcel composites

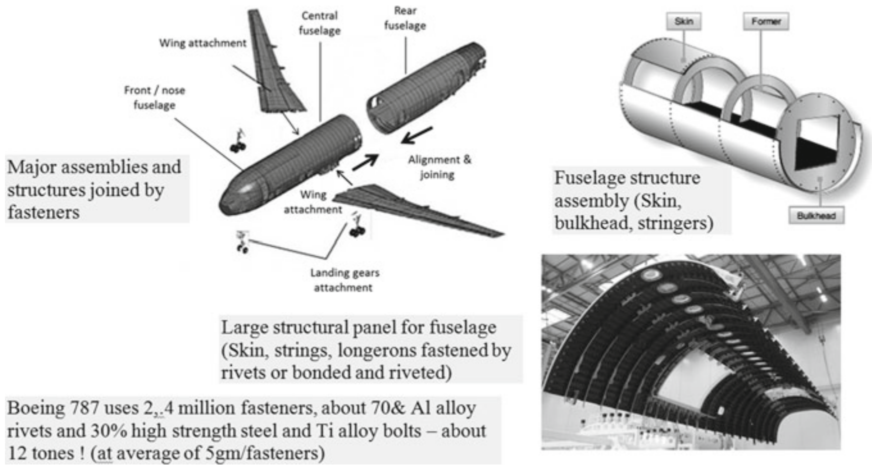

Fig. 6.7 An illustration of aircraft structures using rivets and other fasteners

A significant engineering intervention to reduce aircraft weight is reducing the weight of engines, equipments and systems, weight of cable looms and aircraft paint etc. Engine designers use techniques as discussed above for materials and manufacturing processes to reduce the weight of engines and increase thrust to weight ratio of engines. Aircraft designer will have to choose the most suitable engine from what is available keeping in mind the need for weight optimization. Alternately, if finances are available, contract for developing a suitable engine with the required power with weight optimization.

Air conditioning and pressurization systems and various electro mechanical and electronic equipments and systems offer a significant challenge and opportunity to reduce weight through miniaturization using latest technology of intelligent materials, sensors, MEMs. Replacements of conventional cockpit instruments by developing modern glass cockpit with multifunction displays can reduce weight considerably. Aircraft cable looms/electric harnesses is another area for weight reduction. Aircraft cables measure up to several kilometers and add significantly to the weight. Development and use of ultra-light cables using latest materials and process innovations and technology can reduce weight of cables.

Development of lighter aircraft paints can also contribute to reduction in the aircraft weight. It is stated that Boeing 777 used about 215 kg of paint per aircraft and Boeing 747 about 250 kg. R&D and innovations in using nano-materials for pigments and nano coating technology can lead to lower weight paints with larger spread and lead to substantial weight reduction.

Carbon nano-tube reinforced polymer composites (CNRP) and carbon nanotube aluminum alloy composites are considered to be promising future materials for aerospace structures. These are estimated to be 60–100 times stronger than steels and weigh 70–80% less than steels. Based on theoretical analysis carried out by experts (Sarah et al. 2012), use of such nano material composites for aero structures of Boeing 747, Airbus A-320 and a few other smaller aircraft can realize substantial weight reduction of the order of 20% on a volume for volume basis. Redesign of structures, taking advantage of the higher strength to weight ratio (specific strength and stiffness), fatigue strength and resistance to crack propagation etc. has potential for much higher weight reduction. However it will remain a designers' dream for at least another decade until materials scientists and engineers develop and mature this technology for commercial production. A summary of a systematic step by step approach to weight reduction and optimization of aircraft as discussed in detail in the above sections is illustrated in Fig. 6.8.

6.3 Weight Reduction Strategies Applications in ALH and LCA: A Case Study

India's Advanced Light Helicopter (ALH/DHRUV) and the Light Combat Multirole fighter aircraft (LCA/TEJAS) are two recent successful projects for which aircraft and equipment designers of HAL/ADA worked along with the materials scientists and engineers from industries, R&D and academic institutions to meet the challenges in realization of the objectives. In both the cases, light weighting was an important goal to enhance operational performance. ALH has been developed by HAL as a multirole-multi mission cost effective helicopter in the 5 to 6-ton category to meet the requirements of Armed forces (Army, Navy, Airforce) and paramilitary (BSF&CG), and also civil/operators (2 + 12 seats), and for search and rescue and air ambulance roles. Figure 6.9 shows advanced technology features of the basic helicopter. It

Weight Optimization of Aircraft – Summary
Aerodynamic Configuration design – size & shape optimization
Detailed Structural design ➢ Reduction in thickness of components (use of materials with higher specific strength & specific modulus) ➢ Use of sandwich structures with light weight honeycomb/foam cores and optimize face sheet thickness ➢ Provision of cutout and lightening holes ➢ Local thinning by selective chemical milling
Innovative Design using innovations in manufacturing processes ➢ Integrally milled structures ➢ Bonded structures ➢ Co-cure & Co-bonding ➢ Single Moulding of large structures
Structural Design optimization considering other properties such as buckling, fracture toughness, fatigue, fatigue crack propagation, corrosion / stress corrosion etc
Reducing sub-assemblies, reduce joints and save on the weight of fasteners
Reducing weight of instruments / equipment through miniaturization (sensor / MEMs technology)
Reducing weight of electric harness (cable looms) by Innovations in materials & process to develop light weight cables
Reducing weight of paints (innovations in developing light weight paints and coating process for thinner / efficient coatings)

Fig. 6.8 An approach to step by step weight optimization of aircraft

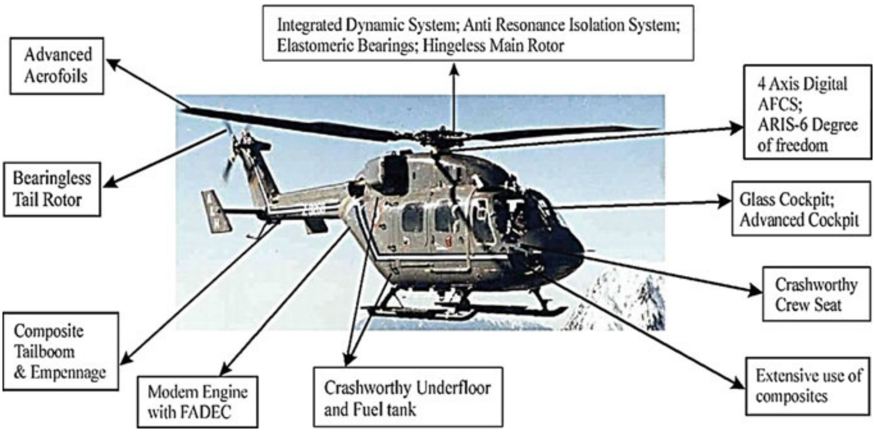

Fig. 6.9 ALH basic version

has been acclaimed as a World-class helicopter using latest technologies and holds world record for high altitude (above 7000 m) performance in its category. A detailed account of the development, materials and technologies of this world-class helicopter is given in the book ‘DHRUV’ (Krishnadas Nair et al. 2014) published by Harishree Publications/Society for Aerospace Studies. It was the only helicopter (from among Indian, European, American and Russian origin helicopters in use in India for military and civil transport) which could fly at the high altitude under adverse weather (rain and storm) conditions and rescue disaster victims during the ‘Uttaranchal’ landslide in June/July 2013. This led to Indian team receiving the prestigious world award for the rescue and relief operation from the American Helicopter Society.

Light Combat Aircraft (LCA) is another major achievement for the aerospace and materials Scientists/engineers. Figure 6.10 illustrates some of the advanced technology features of LCA. It is designed as a highly agile, and worlds lightest advanced technology multi-role combat fighter in the empty weight category of 6000–7000 kg and a speed of 1.5 M and a service cealing of 16 km.

In both these above projects weight optimization was aimed during the design and prototype development/manufacturing phases to achieve minimum weight maintaining structural integrity and the high performance requirements. Principles and processes as outlined earlier to design with alloys of high strength to weight ratio, provision of lightening holes/cut outs, integral milling, local thinning, etc., and use of FRP composite structures, bonded honeycomb sandwich structures were applied.

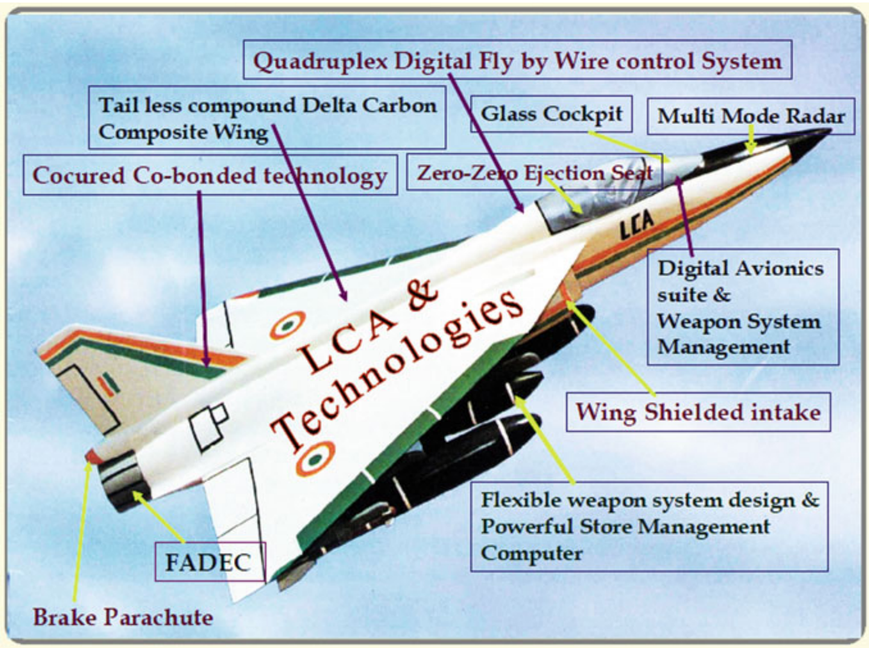

Fig. 6.10 Advanced technology features of LCA Aircraft

Also innovations in design to reduce the number of sub-assemblies using technologies such as co-cure and co-bonding and large single moulded structures in composite materials were employed.

A number of high strength alloys were indigenously developed and utilized, process technology for forging and large casting of such alloys to optimize structure and properties were developed and employed. Weight reduction was achieved by reducing the number of joints for structural assembly and thereby reducing the number and thus the weight of fasteners. Several of the electro-mechanical systems and instruments were indigenously designed and built with miniaturization to save volume and weight by employing sensor and MEMs technology. The weight of electrical harness was reduced by indigenously developing very light weight cables. Even some efforts were made to reduce the weight of paints successfully. These are briefly discussed in the following paras.

Aluminium alloys, most promising ones listed in Table 6.1, account for over 40% of structural weight for both ALH and LCA. R&D at HAL, DMRL, OFAJ and NAL have led to indigenous development of a number of these alloys and process technologies for precision casting, forging, extrusion, welding, heat treatment etc. These have been used for earlier aircraft projects designed and built in India and also produced under license. This was fully utilized for the ALH & LCA projects. Al-Cu-Mg-Si-Mn alloys (2014 and 2024) were selected and used for primary structural sheet metal components in the fuselage. Aluminum magnesium alloys (5083 and 5086) are used for welded tanks, heat exchanger structures, hydraulic and fuel systems etc. Higher load bearing, thicker sections such as bulkheads/frames, spars, and longerons were machined from 2024 plates. Extrusions with special profiles

Table 6.1 Comparison of properties of some high strength aluminium alloys for aerospace applications

Properties	2014-T6	7010-T7452	7050-T7452	7085-T7452 (Al-7.0zn-1.5Mg-1.65Cu-0.12Zr)	Al-1.8Li-2.7 Cu 0.7 Zn
Sp. Gravity (δ)	2.79	2.81	2.81	2.85	2.62
Elastic Modulus (E) GPa	72.34	70.6	70	70	78.4
Sp. Modulus (E/δ)	25.9	25.1	24.9	24.6	29.9
Yield Strength (0.2% PS) (Sy) MPa	379	425	421	462	496
Sp. Strength (Sy/δ)	135.8	151	150	162	189.3
UTS MPa	434	490	490	510	552
% Elongation	8	7	8	9	7

depending on the stiffness and strength required were made of 2024 and 7010 alloys. Large section extrusions in 7010, 7050 and 7075 (modified) were developed as forging stock for making forged and machined high strength—light-weight structural brackets, fittings, landing gear parts, wing attachments and the like. Scientists from DMRL and engineers from HAL and OFAJ Nagpur worked to develop the process of extrusion and controlled stretching to minimize residual stresses and coarse grain envelop and achieve improved dimensional stability and fatigue strength and fatigue life. A modified 'C-process' and near Iso-thermal forging technology were developed for large forgings such as Fin and Wing root fittings and brackets for LCA and structural forgings such as brackets, fittings, links for ALH.

Magnesium alloy castings are potential weight savers as substitute to aluminum alloy castings for various applications. A number of these alloys and process technology have been developed by HAL F&F, DMRL Hyderabad and NML, Jamshedpur and some of these were utilized for earlier aircraft projects. Some of these were selected for the ALH and LCA project for various types of cast components to take advantage of weight saving. A major challenge was the development of the large main gear box casting for the advanced light helicopter in magnesium zirconium alloy–RZ5. Such a large size casting, 900 mm $\times$ 810 mm $\times$ 408 mm weighing over 56 kg was never attempted before. The gear box housing casting for the LCA was even more complex in shape with much more variations in thickness as well as internal cooling holes for passage of cooling oil. Design of mould with chills in selected areas to ensure appropriate cooling rate to get sound casting would have required an incredibly large number of attempts. F&F division supported by the Scientists from Central Laboratory, both of NAL, Bangalore, optimized design of mould, melting and casting parameters using IT tools and techniques to stimulate the process and thereafter a few trials, followed by extensive X-ray radiography and cut-up tests to develop sound radiographic quality castings with the required structure and properties. This is considered as a major achievement as such large castings in magnesium alloys for aerospace applications were produced first time.

Considering the high strength to weight ratio of Titanium alloys, Ti-6-Al-4V and Ti-3Al-2.5V alloys were extensively used for fittings and brackets, high strength fasteners, control rods, etc. substituting alloys steels. Use of Titanium alloys resulted in approximately 30% saving in the weight as compared to alloy steels. Titanium alloy sheets were used in the hot zones near the engine. Titanium rivets and fasteners were used in place of aluminium and steel fasteners for joining and assembly of carbon fibre reinforced plastic laminates because of the superior resistant to the galvanic corrosion. Several of the Titanium alloys in the sheet and plates, billets and rod form were developed and manufactured by MIDHANI, Hyderabad with active support from Defense Metallurgical Research Laboratory. Forging process to get the desired structure and properties was developed and optimized for various components by HAL, F&F division.

In the field of steels, Indian steel industries had already made significant contributions in the development of various types of alloy steels for automobile and other engineering applications. HAL has been using imported aircraft quality steels for its several licensed projects. These were of Russian, American and European specifications and each required only in small quantities. In an effort to indigenously develop equivalents a study for rationalization and variety reduction of alloys was made and many of the aircraft quality Cr-Mo and Cr-Mo-Ni, and Cr-Mn-Si low alloy steels including micro alloyed HSLA steels and high temperature heat resistant steels were developed and manufactured through the Indian steel industries. Such earlier R&D and indigenous development became very useful for the ALH and LCA projects. Maraging steel of different grades was required for aircraft and space projects. R&D at DMRL, MIDHANI and HAL ably supported by materials scientists from ISRO led to the development of Maraging steels and forging technologies. Forged and machined fittings requiring high strength, such as actuator and landing gear components, bracket and fittings and high strength bolts were made of these steels particularly micro alloyed high strength low alloy steels and maraging steels.

Carbon fibre and glass fibre composites offered a great opportunity to the designer to utilize and substitute aluminum alloys and steels in a variety of applications. In case of ALH these included various fuselage sections, such as cockpit outer shell side panels, Tail boom shells, vertical fins as well as main Rotor blade and several thick solid moulded structures such as top and bottom hub plates. In case of LCA these included CFRP wings skins, fuselage side panels, Fin and Rudder, Interspar box etc. The metal honeycomb sandwich composite structures with very high rigidity to weight ratio allowed extensive applications for floor/boards floor beams and such other structures in both LCA and ALH. Designers choice of materials considering the specific strength and specific modulus and designing with these materials and also using bonded sandwich structure resulted in considerable weight savings.

Development of carbon brake by DRDO Scientists along with aircraft designers was a major achievement and also contributed to weight reduction of LCA. Iron based copper based metal ceramic brake pads were used for HAL designed and built aircraft as well as those produced under license, such as Jaguar, Mirage, SU-30 etc. Technologies for these were developed by DMRL and HAL aircraft designers working together along with HAL F&F division. Instead of using this technology of metal ceramic brake pads, LCA designers took up the task of developing the carbon brake disc, in which PAN based carbon fabric was used as reinforcement in a carbon matrix. These brakes were developed as per MIL-W5013 and were superior in performance with added advantage of lower weight about 13 kg almost one fourth of the iron based brake pad.

Designer along with materials technologist/engineers made use of the co-cure and co-bonding and moulding of large FRP composite structures and reduced the number of subassemblies and riveted joints substantially for LCA and ALH structures. Co-cure and Co-bonding technology was developed by NAL and Moulding technology for large structures by layup process, and Resin Transfer Moulding by HAL. This has brought down the number of subassemblies to about 60 for ALH, less than 50% as compared to conventional design for such sized helicopters. In case of LCA the number of sub-assemblies was reduced to approximately 50% as compared to conventional design of similar size fighter aircraft. These led to considerable reduction in the number of fasteners 1.6 lakhs for LCA as compared to 2.5 to 3.0

lakhs for equivalent fighter aircraft. ALH used about 21,000 (19,000 rivets + 2000 other fasteners) per helicopter, as compared to about 60 to 80,000 for similar sized helicopters of conventional design.

R&D for light weight aerospace cables was undertaken by M/s. Sanghvi Aerospace Pvt. Ltd and later by M/s. Radiant Cables. Advances in materials technology included the development of silver coated copper wire and higher degree of compaction (instead of the earlier tin coated copper wire) and use of advanced lighter weight polyimide + PTFE composite insulation (as against the earlier PVC/PTFE insulation). These advanced technology electric cables saved 20–25% in weight and volume with superior performance such as temperature rating, abrasion resistance, dielectric strength, chemical resistance and excellent flexibility to make electrical looms/harnesses.

Avionics and electro-mechanical systems and such other LRUs represent a substantial percentage of the equipped empty weight of the aircraft (EEW) including airframe structural weight, engine and equipments and electric harnesses etc. So the designers looked for reducing the weight of the equipments and systems. Miniaturization in avionics equipments and systems was addressed for reduction of volume (size) and weight and achieved in several such items developed by HAL R&D using smart materials/sensors based MEMs (Micro electro mechanical system) technology. This reduced the weight of LRUs for ALH to about 18% of the EEW and for LCA about 24%.

Weight of paint may represent a much smaller % of the aircraft weight. For ALH size of helicopter it will be of the order of 20 kg and for LCA size aircraft about 40–50 kg. While there are several types of paints such as Nitrocellulose, Acrylic, Epoxy and Polyurethane, the latter two are preferred because of their superior properties. Other constituents of the paints are pigments, solvents and curing agents. Materials scientists and designers worked with industry for lighter weight paints with more spread. M/s. Southfield Paints Ltd in Bangalore has achieved success and have been able to reduce weight of paints from 50 to 55 g/m^2 to 35 to 40 g/m^2. Use of such paints reduced consumption and so the weight of paint per helicopter to 12.5 kg and about 32 kg per LCA. Further development using nano-materials science has potential for further reduction.

6.4 Conclusions

In conclusion it may be seen that light weighting of aircraft was achieved by reduction in structural weight by designing with materials possessing high strength to weight ratio, high modulus to density ratio, engineered materials such as honeycomb sandwich structures, and by designing to reduce the number of sub-assemblies by innovative process technologies such as large composite mouldings, co-cure and co-bonding, and thus reducing the number and weight of fasteners, reducing the weight of equipments by miniaturization of equipments using MEMs technology, and by reducing the weight of electric looms by advanced technology in materials, and even making a mark on the reduction of the weight of paints.

Materials Scientists/engineers and aircraft designers can work together developing and using innovations in materials, manufacturing technology and design philosophy to achieve and continue to achieve 'Light Weighting of Aircraft'.

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Chapter 7
Trends in Automotive Light Weighting

Aravind Vadiraj, Mathew Abraham and Aravind S. Bharadwaj

Abstract Automotive industry globally is under pressure to cut emissions and improve average fuel economy of their vehicle models. This will address both the efforts to mitigate climatic change and huge oil import bills. Light weighting of vehicles can be achieved through architectural changes, material substitution and advanced manufacturing processes. Advanced materials like High strength steels, Aluminium and Magnesium alloys, composites along with advanced manufacturing processes like hot-stamping, vacuum casting, laser and adhesive joining can effectively reduce the vehicle weight but at a cost higher than current materials and designs. Premium segment vehicles have been using these technologies to substantially reduce vehicle weight and market their products successfully in many countries. Indian OEMs like Mahindra & Mahindra Ltd. have also demonstrated as well as implemented several light weight technologies in their mass market vehicle models. This paper provides many such interesting examples along with details on different materials and manufacturing processes.

Keywords Light weight · Materials · Manufacturing · Emissions

7.1 Introduction

7.1.1 Global Emission Trends

Carbon dioxide, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride are six types of harmful greenhouse gases (GHG) affecting life on this planet (http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Transport_energy_consumption_and_emissions). Road transportation is understood to be responsible for significant atmospheric pollution. Carbon dioxide is a part of natural carbon cycle within earth's crust, flora/fauna and the oceans. Electric power

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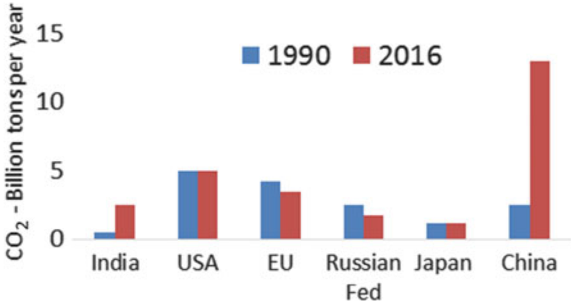

Fig. 7.1 CO_2 emissions from fossil-fuel use and cement production of top 5 countries along with European Union for the year 1990 and 2016 (Trends in Global CO_2 Emissions 2016 Report)

plants, transportation and general industries emit significant amount of carbon dioxide (http://www.epa.gov/climatechange/ghgemissions/gases/co2.html). Atmosphere scientists and experts argue that the main cause of global warming is from automotive vehicles and to some extent from industrial sources. Therefore, the transportation has to be more sustainable which contributes positively towards environment, society and economy.

CO_2 emission have increased enormously in the last two decades. Figure 7.1 compares CO_2 emissions from fossil-fuel use and cement production in 1990 and 2016. It is observed that the levels have quadrupled for India and China. While USA, Russian federation, European Union (EU), and Japan shows small changes in the trend. Rapid industrialization in China for last two decades have resulted in alarming levels of emissions prompting all other nations also to take serious steps to control and reduce harmful emissions for sustaining life and ecology.

7.2 Fuel Consumption Trend for Road Transportation

Leaded and unleaded petrol, diesel, motor spirits and LPG are the main petroleum products used by majority of the road transport vehicles across the world. Oil consumption globally is projected to increase from 34 million barrels to 43 million barrels from 2010 to 2035 (http://www.statista.com/statistics/307198/forecast-of-oil-consumption-in-road-transportation/). India is heavily dependent on oil rich counties like Saudi Arabia and Iran. India ranks third in oil import with $60 billion (http://www.worldstopexports.com/crude-oil-imports-by-country/). Therefore, a lot of currency reserves are being spent on imports with rising demand for fuel in India. The fluctuating currency least favors the economy with rising imports. Hence it is imperative to adopt all possible automotive technologies that can reduce oil import bills.

7.3 Light Weighting: A Need Today More Than an Option

Mass along with aerodynamic and rolling resistance tend to decelerate the moving vehicle. These are main resistive forces which reduces fuel economy and increases emissions. Therefore, lighter mass makes the vehicle more fuel efficient along with many other secondary benefits. Every 100 kg mass reduction will improve 6–7% fuel economy and reduce 9 g/km of CO_2 (Belhabib et al. 2011). For electric vehicles, total range significantly improves by light weighting. The secondary benefits from light weighting would be reduced braking distance, improved ride and handling, improved power to weight ratio and safety of vehicle along with scope for downsizing of other aggregates.

A lighter vehicle architecture can be realized from (a) light weight designs, (b) lightweight materials, and (c) alternate manufacturing processes. Materials as well as design go together always in developing a specific architecture. A Monocoque body would always be lighter than body-on-frame architecture. In any passenger vehicle, body, chassis and power train takes up major share of its overall weight (about 50%) offering a very good scope for weight reduction in these areas. Weight reduction strategies normally comes with certain trade-offs like higher cost and supply chain complexities which limits them to only certain premium vehicle variants. Top variants with many advanced features adds mass to vehicle which can only be offset with light materials.

Light materials have enormous potential for reducing overall mass of the vehicle. High strength steels although not a light material has a weight saving potential anywhere from 15 to 26% (Marathe et al. 2013). Table 7.1 shows various grades of Advanced High Strength Steels (AHSS). Conventional bake hardened (BH) and High Strength Low Alloy (HSLA) grades steels have already been deployed in the present models. First generation of advanced high strength steels like Dual phase (DP), Complex Phase (CP) and Transformation Induced plasticity (TRIP) grades are currently being explored for applications. They are cost prohibitive apart from posing difficulties in forming as well as manufacturing. Second generation of AHSS like Twin induced plasticity (TWIP) and austenitic stainless steels are in the pilot scale of research today (Kuziak et al. 2008). The higher strength translates into better fatigue and crash performance.

Aluminium and Magnesium alloys with more than one third density competes strongly with steels. Some of the automotive grades of Aluminium and Magnesium alloys have weight saving potential of 30–50% (Marathe et al. 2013). Advanced grades of Aluminium alloys have specific stiffness of 2.6 and specific strength of 12 combined with excellent corrosion resistance and recyclability. They are available in the form of sheets, castings and hollow extrusion which are most common forms used for automotive applications. The components which can be made with aluminium alloys are panels like roof, door, floor, and structural components like knuckles, control arms etc. The primary issue of aluminium alloys are joining, low wear resistance, higher cost, lower strength compared to steel (Kuziak et al. 2008).

Table 7.1 Grades of AHSS (http://www.metalformingmagazine.com/magazine/article.asp?aid=9422)

Steel grade	YS (MPa)	UTS (MPa)	Total EL (%)	n-value (5–15%)	r-bar	Application code
Mild 140/270	140	270	38–44	0.23	1.8	A, C, F
BH 210/340	210	340	34–39	0.18	1.8	B
BH 260/370	260	370	29–34	0.13	1.6	B
IF 260/410	260	410	34–38	0.20	1.7	C
DP 280/600	280	600	30–34	0.21	1.0	B
IF 300/420	300	420	29–36	0.20	1.6	B
DP 300/500	300	500	30–34	0.16	1.0	B
HSLA 350/450	350	450	23–27	0.22	1.0	A. B, S
DP 350/600	350	600	24–30	0.14	1.1	A, B, C, W, S
DP 400/700	400	700	19–25	0.14	1.0	A, B
TRIP 450/800	450	800	26–32	0.24	0.9	A, B
HSLA 490/600	490	600	21–26	0.13	1.0	W
DP 500/800	500	800	14–20	0.14	1.0	A, B, C, W
SF 570/640	570	640	20–24	0.08	1.0	S
CP 700/800	700	800	10–15	0.13	1.0	B
DP 700/1000	700	1000	12–17	0.09	0.9	B
Mart 950/1200	950	1200	5–7	0.07	0.9	A, B
MnB	1200	1600	4–5	n/a	n/a	S
Mart 1250/1520	1250	1520	4–6	0.07	0.9	A

Application code: A—Ancillary parts, B—Body structure, C—Closures, F—Fuel tank, S—Suspension/Chasis, W—Wheels

Some of the grades of Aluminium alloys uses in automotive applications are as shown in Table 7.2.

Magnesium alloys are much lighter than aluminium and some grades of polymers and composites. Table 7.3 shows various grades of these alloys. Their specific stiffness of 2.6 along with highest specific strength of 14 allows them exhibit highest strength to weight ratio of all other materials. Most probable applications are steering column, steering wheel, door inners, seat frame, instrument panels, CCB and transfer case. Currently the problems faced by Magnesium alloys are poor corrosion resistance, poor creep resistance, poor formability and high cost (Kuziak et al. 2008).

Table 7.2 Grades of aluminium alloys for automotive applications (https://www.slideshare.net/vinayakmayank/mg-alloys)

Alloy, temper	Yield strength, KSI	Tensile strength, KSI	Total elongation, %	Minimum bend radius (90° bend)	Cutting clearance per side, %t
3003-0	5	14	25	0	5%
3003-H14	17	20	5	0	6%
3003-H16	21	24	4	1t	7%
5052-0	9.5	25	19	0	6.5%
5052-H32	23	31	7	1t	7%
6061-0	12 max	22 max	16	0	5.5%
6061-T4	16	30	16	1t	6%
6061-T-6	35	42	10	1.5t	7%

Table 7.3 Grades of magnesium alloys (http://www.metalformingmagazine.com/magazine/article.asp?aid=9422)

Alloy	Tensile strength		0.2% yield strength		
	ksi	MPa	ksi	MPa	% elongation (in 50 mm)
Die castings					
AM60A-F	32	220	19	131	8
AS41A-F	31	214	20	138	6
AZ91D-F	34	234	23	158	3
Sand and permanent-mold castings					
AM100A-T6	35	241	17	117	2
AZ63-A-T6	34	234	16	110	3
AZ81A-T4	34	234	10	69	7
AZ91E-T6	34	234	16	110	3
AZ92A-T6	34	234	18	124	1

Reinforced polymer composites like GFRP and CFRP have highest weight saving potential of more than 60% (Marathe 2013). The greatest advantage of polymer based material is its design flexibility, ease of manufacturing and electrical insulation. The most probable applications of these materials are in panels, trims, seats, floor and roof. Some of the issues faced are lack of customer acceptance, cost, fatigue, recyclability and inflammablity (Kuziak et al. 2008).

The design of part based on each of these materials would vary significantly due to differences in mechanical and physical properties. Therefore it is imperative to redesign the entire vehicle or part considering this fact.

7.4 Specific Case Studies on Application of Lightweight Materials

7.4.1 High Strength Steels

There are several case studies which clearly depicts various light weight options in terms of design along with light materials. ULSAB research paper shows BIW design with AHSS has resulted in 17–25% mass savings corresponding to a total vehicle weight reduction of 9% (117 kg) and 2.2 tons of CO_2 emission reduction per vehicle in its whole life cycle (Huetter 2015).

Nissan Maxima (2016) is 36 kg lighter than its 7th generation model (Hirsch 2011). A significant weight was reduced by using 1180 MPa steel in roof rail, A and B pillars. More than 55% of the car was constructed with steels of strength level in the range of 370–390 MPa. Nearly 15% of the structure is from 980 MPa or higher steel and 16.6% from 590 MPa steel. In the under body structure, more than a 25% of the car is made with 590 MPa steel, 7.7% is 780 MPa steel, and another 6.2% is from 980 MPa or higher steel which includes 2.2% die-quenched 1,350 MPa steel. Less than half is actually made from 390 MPa steel (Hirsch 2011). In 2012, a typical European car body had 15–55% of BIW weight from AHSS/UHSS/PHS. Normally the use of HSS or AHSS is combined with advanced manufacturing process. Some examples are: (a) The roof rail and front side inner members can be thin walled hydro formed part, (b) Hot stamped members to resist crash, (c) Partially quenched rear floor side member, (d) High strength steel from 590 to 1147 MPa for BIW panels.

7.4.2 Aluminium Alloys

Aluminium alloys are the material of choice for both mass market models like Ford F-150 and premium segments like Audi, Benz and Land Rover. The "Torquenews" reports some of the disclosed details of weight brake-up of 2015 model of Ford F150 compared to 2014 model. Ford has introduced several light materials and design changes in many areas of the vehicle to realize more than 300 kg of kerb weight reduction. Although body is wholly made from Aluminium panels, the chassis has significant quantity of high strength steels. Body and chassis combined together have reduced more than 200 kg of weight. More than 10 kg have been reduced by substituting steel with aluminium alloy in steering knuckles. Magnesium cover of the four wheel transfer case has reduced 1.7 kg. They have also made several design changes to reduce weight. Design changes in front bumper and rear differential case has reduced 1.2 and 15.8 kg respectively. Design changes in front and rear seat has reduced 14.3 and 6.6 kg respectively. Electronic parking brake instead of mechanical unit has reduced more than 12 kg. The underpinnings for the dash board is lighter by 1.1 kg.

The use of aluminium in new European models increased from 62 kg in 1990 to 132 kg in 2005 (Gaines et al. 1996). An optimized car design with significant Aluminium content has been established for European cars which are as follows: (a) 69 kg in powertrain aggregates like engine block and cylinder head, transmission housings, fuel system, liquid lines and radiators, (b) 37 kg in chassis and suspension system such as cradle, axle, wheels, suspension arms and steering systems, and (c) 26 kg in body parts and sub-systems such as bonnet, doors, front structure, wings, crash protection countermeasures, bumpers and interior trim (Gaines et al. 1996).

Aluminium alloys are actually more than capable of delivering exceptional weight savings required for automotive BIW structure. Aston Martin Vanquish (2001) with an extrusion intensive BIW weighs only 145 kg excluding closures and outer skin and consists of 40 extrusions (100 kg) and 40 sheet parts (45 kg) using rivets and adhesive bonding for joints. BMW Z8 Roadster has BIW mass of 300 kg with 86 straight and 24 bent extrusions with MIG weld joints and 1000 rivets. BMW 5 series models was able to achieve a weight of 47.6 kg in their aluminium intensive front-end structure made exclusively from extrusions, castings and sheet metal with a 30% weight saving compared to steel. Such type of construction satisfies all the necessary requirements with respect to the strength, fatigue, stiffness, formability, reliable processing ability as well as good corrosion resistance. The 2002 Audi A8 (D3) utilizes space frame concept with BIW mass of just 277 kg consisting of 59 extrusions (61 kg). It has 819 castings with 39 kg and 170 sheet parts with 177 kg. The jointing methods used are 2400 rivets, MIG welds, Laser welds, Laser-Hybrid welds, Roll-folding, adhesive bonding. With all the above, it weighs 245 kg (40%) lighter than its steel counterpart. The AUDI R8 BIW only weighs 212 kg. The Jaguar XJ Model (2002) with Aluminium monocoque BIW has mass of only 295 kg, consisting of 22 extrusions with 21 kg, 15 castings with 15 kg and 273 sheets with 259 kg weight. Adhesive, rivets (3000 pcs), clinching and MIG welding are the joining methods used. Audi A6 (2011) comes with 13.5% aluminium alloy (6XXX series) in its BIW for significant weight reduction (Gaines et al. 1996).

All aluminium chassis can achieve up to 40% weight savings in comparison to mild steel apart from improving the dynamics, ride and handling, safety due to reduction in unsprung mass. Alloys like AA 5049 (AlMg2Mn0.8) and AA5454 (AlMg3Mn) having good formability and weldability, high strength after forming, and outstanding corrosion resistance, also in the uncoated condition are generally used (Gaines et al. 1996).

For doors, closures and outer panels, a heat-treatable aluminium wrought alloy generally from 6000 series as well as non-heat-treatable alloy from 5000 series in typical sheet thicknesses of between 0.8 and 1.25 mm are used. Surface finish is very important along with good formability, buckling strength, proof strength, and thermal behaviour such as age-hardening or softening during paint baking or service life. General motors have reduced approximately 25 kg per vehicle from their Cadillac CTS (Gen 2-2011) with aluminium alloy (Gaines et al. 1996).

7.4.3 Magnesium Alloys

Magnesium alloys are not currently used in large quantities for auto parts. They are generally limited to die cast parts globally. Magnesium alloy sheets can be used in non-structural or semi-structural applications. Extrusions can very well be used in structural applications such as space frames. Fabrication and joining for Magnesium alloys is very easy and can be done in single step compared to Steel. However, part fabrication must be done at elevated temperatures (200–315 °C) due to its crystal structure and does not require very capital intensive machinery as done in fabricating steel parts. But still a considerable investment would be needed if automakers were to shift to Magnesium for major body parts. With possible improvements in hot-forming, the operating costs may be lower for Magnesium parts compared to steel parts. One of the Volvo's concept car applied several lightweight materials, including about 50 kg of Magnesium alloys for wheels, chassis, and engine block, and was estimated to have a lifetime energy consumption less than 60% that of an equivalent sized conventional automobile (Gadvi and Chaitanya 2015).

7.4.4 Carbon Fibre Composite

Carbon fibre composites are much stronger and lighter than its metallic counterparts. They have been used for over many decades in sports cars. BMW i3 has carbon fibre in supporting roof pillars and door frames. Steel and aluminium alloys have been used in chassis for its i3 electric model. It weighs at least 250–350 kg lesser because of carbon fibre panels. The crash member is also made from carbon fibre composite. For the Alfa Romeo 4C (Type 960), the chassis of the car weighs only 65 kg (Spider's chassis weights 107 kg) with a single carbon fibre body. The outer body is a composite material (SMC) and is 20% lighter than steel. The stability of the vehicle is quite comparable to steel and better than aluminium. Chevrolet Corvette Z06 (1451 kg) is one of the lightest sports cars available in America with best power-to-weight ratios of 6.33:1. The C6 Z06 model introduced in 2006 has aluminium-based chassis structure with greater percentage of carbon fibre body panels. It weighs 30% lesser compared to the old model. Magnesium has been used in roof structure, engine cradle and suspension attachments. Carbon fibre panels has been used in front fenders, front wheel houses and rear fenders (Gaines et al. 1996).

7.4.5 Light Weight Engineering Plastics

Engineering polymers is the second most common class of automotive materials after metals and alloys. An average vehicle uses about 150 kg of plastics and plastic composites versus 1163 kg of iron and steel. Currently it is moving around 10–15%

of total weight of the car. Plastics are used in both exterior and interior components such as bumpers, doors, safety and windows, headlight and side view mirror housing, trunk lids, hoods, grilles and wheel covers. Three out of the available 13 different polymers make up to 66% of the plastics used in a car which are polypropylene (32%), polyurethane (17%) and PVC (16%). Light weight solutions in plastics can be achieved by application of polymers with lower density and comparable properties, natural fibres instead of glass fibres filled plastics, sandwich panels with cellular/honeycomb structures, gas or water assisted injection moulding for producing hollow structures and foamed polymers. Cellular and hollow structure polymeric materials offers thermal insulating properties.

7.5 Multi-material Design Concepts

Multi-material design methodology carefully balances the advantages of material, manufacturing costs, performance, safety and life-cycle of the vehicle. For example, BMW 5-E60 employs 20% deep drawing steels, 42% medium high strength steels, 20% high strength steels and 18% aluminium alloys. The front-end structure has 16.4 kg of steel and 29.4 kg of aluminium parts in the form of stamped sheets, extrusions, high-pressure die cast parts, and hydroformed tubes. In the case of 3rd generation Audi A8, so called hybrid construction allowed the use of lightweight materials for high volume production. Large sized aluminium castings has been employed for selective areas like front and rear chassis legs (1.4 m long), the front suspension mounts, and the base of the A-pillar and the front section of the transmission tunnel. The door again is one piece casting and rest of the body structure like sills, roof structure and floor sections are made of aluminium extrusions. The B pillar is steel of varying thickness without TWB (Gaines et al. 1996). The real challenge of multi-material design concept is in joining of materials with large differences in their physical and mechanical properties.

7.6 Light-Weighting Through Manufacturing Processes

7.6.1 Hydroforming

Hydroforming process has been applied in various fields, such as bicycle, automotive, aircraft and aerospace industries for the purpose of light weighting by eliminating joints. Tube and sheet hydroforming has numerous advantages, like decrease in number of parts and tool cost, component weight, increased structural stability, strength and stiffness of the formed parts, uniform thickness distribution and lesser secondary operations etc. compared to conventional manufacturing via stamping and spot/MIG welding. Chassis can be hydroformed as a single part instead of pressing in different sections and joining by welding. Considerable mass can be saved by eliminating the flanges needed for welding or applying down gauged steel. Compared with conventional design, the hydroformed parts are approximately 30% lesser in weight, 20% cheaper in cost with 60% less tooling cost (Gaines et al. 1996). Hydroforming permits manufacturing of more complex shapes with integrated structures showing higher stiffness and crash behaviour. The limitations of this process are part buckling, wrinkling, necking, bursting and sidewall fractures.

7.6.2 Hot Forming

A lot of work is currently in progress globally on hot forming of ultrahigh strength and heat treatable 7xxx series alloys covering the basic material characterisation, forming speeds at different temperatures, metal working lubricants, special die designs and FEA analysis on the process. The formability of these alloys is found to significantly increase during deformation at elevated temperatures (240–260 °C). The softening mechanisms reduces strain hardening, extended recovery or recrystallization. The strain levels can go very high (50%) during the process. The sheet thickness used are normally from 0.5 to 6.35 mm. This process is more suitable for alloys with high strain hardening potential (for example: Al-Mg-Mn—5 series alloys). These alloys, at elevated temperatures, show good stability by solute drag effect of Mg atoms with dislocations movement. This sort of diffusion controlled plastic flow is also relevant for high strain rates which makes it suitable for large scale faster industrial production with high strain rates. Hot forming process can reach production rate up to 300,000 per year with full automation. The limitations are higher capital and part cost due to additional heating process, less tolerance due to thermal contraction and warping, scaling and oxidation of work piece and variation of grain structure and properties throughout the material. Hot forming can also produce ultra-high-strength in conventional steels. They are typically used for bumper beams, reinforcements for doors, A and B pillars and some parts of the floor and roof of the vehicle. Hot stamped parts can reduce the weight by up to 50%. The custom-made tempering process targets localized strengthening of a part. There are limitations for hot stamping process. Laser trimming and not traditional trimming has to be done after hardening. Only boron steels and not galvanized or pre-painted steels can be hot stamped. Additional processes like drawing and flanging is not possible after hot stamping.

7.6.3 Vacuum Assisted Thin Wall Castings

Vacuum-assisted vertical die casting process evacuates air from the cavities and feed channels and begins drawing the molten metal from the transfer tube into the injection cylinder. Within few seconds, the required quantity of molten alloy is drawn from the melt, through the transfer tube into the injection cylinder. The movement of the plunger then shuts off the metal flow from the feed tube. The molten metal is injected into the evacuated die to fill the shape and solidify to form the part. A high pressure is maintained on the solidifying metal for certain period of time and then later ejected out into a shuttle tray. The cost of the setup ranges from $50,000 for small parts up to $2,000,000 for very big parts (India mart). The advantages of this process are integration of several parts, good dimensional accuracy, good surface finish, good mechanical properties and reduction in the defects. The disadvantages are high initial cost, complex mould making and this process is only suitable for mass production. Most of the magnesium parts are casted by cold chamber die casting due to process advantages. These parts includes, instrument panel, radiator support, engine cradle, seat frame, engine block, transmission case and oil pan. GM has introduced the first ever high-volume single piece die cast magnesium instrument panel (IP) in 1996 for GMC Savana and Chevrolet Express. This part weighed only 12.3 kg for a thickness of 4 mm forming the largest magnesium die cast part showing 32% mass savings compared to the steel design along with cost savings due to parts consolidation (25 parts vs. 67 parts in steel) (Gaines et al. 1996).

7.6.4 Semisolid Thixo-forming

Thixo-casting process utilizes pre-cast billet with a non-dendritic microstructure heated to semi-solid temperature range before injecting it into a hardened steel die. The properties of the material processed by thixo-forming is close to forging and hence more suitable for suspension parts. The process window for making thixo-cast Aluminium parts will be between the solidus and liquidus lines in the phase diagram. They produce net shape or near net shape components using a shorter processing route compared to gravity casting. They are energy efficient, minimum thermal shocks due to low processing temperature and can produce parts with complex geometries. However, the disadvantages are higher raw materials cost and higher capital investment on the machineries and dies, requirement of highly skilled personnel and much more precise temperature control. Front axle upper wish bone production ready part with 5–10 mm wall thickness was made by thixocasting of A356 Aluminium alloy for Mercedes S class (1998) (Gaines et al. 1996). The final weight of the finished part was only 0.960 kg with a weight benefit of 30–40% over steel.

7.6.5 Extrusions

Extrusion process can create objects of fixed cross-sectional profile. The material is pushed through a die of desired cross-section and will be taken out from other direction. Aluminium extrusions and castings have always been a part of light weight design. Extrusion can produce complex shapes and profiles allowing groundbreaking lightweight design with integrated functions. New car concepts based on the aluminium space frame body architecture and sub-structures like chassis, bumpers, crash systems, air bags, etc. have been developed in Europe using extrusions. Extrusions process enables very high potential for complex designs and functional integration for mass production. Medium strength 6xxx series and high strength 7xxx series age hardenable alloys are generally used because the required quenching occurs during the extrusion process. The cost of machineries required for Aluminium alloy extrusion in India is more than $10 million out of which the press alone would be $3.9 million (Sapa Group). It can produce 1 Ton of extrusions of 50 meters length per hour. The annual capacity is around 20,000 metric tons. Strength and formability is achieved during age hardening step. However, the disadvantages are limited part complexity and uniform cross sectional shapes only are possible. Extrusions are normally used for bumper beams and crash boxes (Gaines et al. 1996).

7.6.6 High Pressure Die Casting

High pressure die casting (HPDC) process is a cost-effective and reliable manufacturing process for production of high volume metal parts with net-shape and tight tolerances. The process consists of injecting certain volume of molten metal alloy into a steel mould at high pressure which gets solidified instantly within few milliseconds or seconds to take the final shape of the component. The part is then automatically extracted from the die. The entire cycle time could last for about 60 to 70 s. The cost of the die-cast machine alone in India ranges from $8000 to $55,000 depending upon the specifications (India mart). The advantages of this process are that they are highly energy efficient and economical with very high production speeds, good dimensional accuracy and stability, good strength and simplified assembly. The disadvantages are higher capital investment, limited to metals with higher fluidity, contains porosities and needs large volume production for cost competitiveness.

Casting comprises highest volume of aluminium components in cars, such as engine blocks, cylinder heads, wheels and special chassis parts. They are also gaining acceptance in space frame structures, parts of axle and other structural components. High pressure die cast Al-Si-Mg-Mn alloys have been developed with good combination of strength and ductility. Alloys with good strength and crash resistance (such as Al-Si9-Mg-Mn) for chassis and BIW applications have been developed (Gaines et al. 1996).

7.7 Light-Weighting Efforts in Indian Automotive Industries

Corporate average fuel economy (CAFE) regulations in the USA has pressurized all the OEMs to develop more fuel-efficient vehicles. But the Indian government at present does not mandate any such stringent regulations. However, Indian OEMs are pushing lighter vehicle for improving efficiency and cut costs. The sixth generation Hyundai Elantra which was launched in India recently has used large quantity of advanced high strength steel (AHSS) for reducing weight. It has 53% of AHSS material both for light weight and crash safety. Maruti Suzuki had started a One Gram One Component Programme targeting to decrease weight of each components by 1 g in 2008. In commercial vehicle segment for example, by changing a liquid container material from steel to plastic, the vehicle can carry 600–800 kg more in payload thereby reducing the cost per ton.

Mahindra & Mahindra is India's most diversified manufacturer of tractors, trucks, passenger vehicles and two-wheelers. They are aggressively leading several programs to light weight their products across all these segments for improving efficiency, cut costs and meeting the upcoming emission norms. A recent light weight initiative called War-on-Weight (WOW) on their model Quanto (now NUVOSPORT) yielded nearly 280 kg of weight reduction through changes in architecture, light-weight materials and design strategies. They have successfully demonstrated BIW parts with composites and Aluminium alloys during WOW initiative. Over the last decade, there has been a shift from mild steel to high strength steels for BIW in several vehicles including the awarding winning XUV 5OO. Almost 25% of high strength steel content has been used in this vehicle. Plastic fenders has been in production for this vehicle since 2011. They have successfully passed the challenges of paint durability and match with rest of the body colour for fenders which is first time in India. Through rigorous design optimization, they could also reduce 12.5% weight in the new 1.5 L Turbo Charger Intercooler engine. It is to be noted that none of the weight reduction strategies implemented so far have compromised the tough and rugged DNA of their vehicles. All these initiatives have been realised within the affordable cost. They are currently pursuing some more parts with advanced engineering plastics and composites. Aluminium and Magnesium alloys for suspension and electrical parts which has shown 40–50% weight savings are being currently explored. There is also an attempt to develop a light weight vehicle through consortium approach where in OEM, suppliers and academic and research institute can come together and contribute their new developments and promote the technology, manufacturing and supply eco-system to make it more affordable in India.

7.8 Summary

Automotive light weighting is imperative to cut emissions and improve average fuel economy. There is an immense pressure globally to address the climatic changes due to greenhouse gases (GHG) out of which CO_2 forms the major portion. Generally 10% reduction in overall weight will give rise to 6–7% improvement in fuel economy and 9 g/km CO_2 reduction. Vehicle light weighting can be achieved through novel architecture design, substitution with light materials like automotive grade aluminium alloys, magnesium alloys, plastics, composites and advanced manufacturing techniques like hydroforming, hot forming, vacuum casting, extrusion etc.

Premium segment models have successfully implemented these methods to substantially realize weight savings in their products. Even in India, OEMs are aggressively pursuing for shedding weight of all their mass market models. Several companies have successfully implemented light weight solutions in their products.

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Chapter 8
Advances in Test Techniques to Characterize Fatigue and Fracture Properties for Safety Critical Applications

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This paper is a review of developments of note at BISS that impact structural integrity. A test system and procedure were developed to determine J_{1c} for the case of a *through* crack in the wall of a pressure vessel subject to *internal pressure*. More recently, an online scanner was developed and integrated with an automated test system to track damage growth in carbon fibre reinforced plastics under static and cyclic loading. By far the most significant development, from a scientific perspective, is a path-breaking discovery that the well-known mean stress (or residual stress) effect on metal fatigue may be attributed to environmental action. A variety of specially designed experiments proved that the mean stress effect becomes negligible in high vacuum. Further research involving the development of a new test procedure led to the establishment of a unique relationship between computed near-tip residual stress and a threshold stress intensity required for the onset of (atmospheric) fatigue crack extension. All this research required concomitant development of test techniques unavailable from the typical 'black box' test equipment associated with conventional fatigue testing.

8.1 Introduction

The long-term potential of a research community is realized through the creation of intellectual property that can add substantial value to existing products and services, as well as creating entirely new ones enjoying the advantage of a unique niche. It is these added values that can make a difference to both the economy as well the advancement of science. Expressed in the Indian national context, a 'Create in India' vision can enrich our societal impact as a community , rather than a 'Make

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in India' approach that only supports licensed manufacturing. The present chapter cites examples from the author's personal experience to illustrate why the 'Create in India' vision is not only important, *but also possible*.

Bangalore Integrated System Solutions (P) Ltd (BISS) was formed in 1992–93 to commercialise test control technology that had been developed and operationalized at the National Aerospace Laboratories, also in Bangalore, India. This technology found a ready market in the defence, nuclear and space sectors, which were achieving steady progress despite the sanctions caused by embargos on our country. For example, the influx of foreign auto manufacturers induced a proliferation of local component manufacturers. These indigenous companies needed sophisticated testing machines to ensure that the quality of their products matched global standards. There then evolved a 'knock-on' effect, whereby (i) local *automobile* manufacturers could have access to high-quality locally-made components, (ii) the local *component* manufacturers became involved in developing locally designed automobiles, and (iii) the local *automobile* manufacturers' R&D departments *also* needed high-quality tools for vehicle development, including testing machines. This evolutionary process served as fertile ground for a local start-up with expertise in test controls (BISS) to grow into a developer, manufacturer and exporter of a vast variety of state-of-the-art, digitally controlled mechanical test systems.

BISS may also serve as a good example of the importance of R&D in accessing the world market for high technology products. Over 60% of BISS personnel are graduate engineers, of whom 25% hold postgraduate degrees. This team has to its credit, a vast array of market-driven inventions and innovations, and also a major scientific discovery. Three particularly important and interesting innovations are described in this chapter. They concern the development of test technologies to meet specific material characterization requirements that cannot be addressed by conventional 'standard products'. One of them led to an important scientific discovery thanks to specially designed experiments involving new automated test procedures. Conventional wisdom associates metal fatigue with cyclic slip. The magnitude of cyclic slip is uniquely related to strain amplitude. Mean stress (or, residual stress) are not known to affect strain amplitude. Yet, their effect on fatigue thresholds is decisive. A description of how this paradox was finally resolved using techniques developed at BISS is forthcoming.

8.2 Determination of J_{1c} for a Pressure Vessel with a Through Crack

The service life of nuclear power reactors is to a large extent limited by the structural integrity of its components. Among these are the zircaloy pipes that carry the nuclear fuel rods and circulating water, which is pressurized to over 100 atmospheres so that it does not boil even at 300 °C. Despite the pipe material's high resistance to in-service degradation, owing to radiation and the possible formation of cracking from internal hydrides, decades of continuous operation carry the risk of an unacceptable loss of residual strength if a pipe becomes cracked. Like all pressure vessels, the pipes must satisfy the 'Leak before break' criterion to ensure that the reactor can be safely shut down in the unlikely event that a hydride-induced crack grows through the wall thickness, resulting in leakage. Nuclear power reactors are equipped with moisture detectors to close this safety loop.

BISS was contracted to design, develop, manufacture, validate and supply a test rig to evaluate the residual (burst) strength of controlled size sections of (irradiated) piping from pressurized water reactors. A detailed description of this project is given in Avinash et al. (2006). Here we present the technical details of interest to the experimental research community.

Figure 8.1 is a schematic of a hollow cylinder with an axially-orientated through-thickness crack. 'Handbook' solutions are available for the stress intensity factor, K, for a crack in the presence of internal pressure. Also available is the equation that describes the open area formed by the crack with such a pressurized component or specimen geometry. Assuming the crack to take the shape of an ellipse under load, one can derive the equation for crack opening displacement under internal pressure and proceed to describe the compliance function. Thus, in principle, a specimen simulating the configuration shown in Fig. 8.1 can serve the purpose of fracture testing, just like the ASTM standard compact-tension and single edge-notched specimens used by industry and the research community for more general fracture mechanics testing. However, unlike the solutions and equations for ASTM standard specimens, the solutions and equation for a pressure vessel *may never have been experimentally verified*, owing to the difficulties mentioned in the next paragraph.

In contrast to standard laboratory coupons, testing a hollow cylinder for fracture presents several challenges:

- The through-crack needs to be sealed in a manner that satisfies contradictory requirements: (i) it must sustain internal pressure without leakage and (ii) at the same time permit the crack to open and close, firstly to permit fatigue pre-cracking for a valid J_{1c} test; and secondly to permit stable crack growth and automatic crack size (and crack growth increment) measurements during the fracture test.

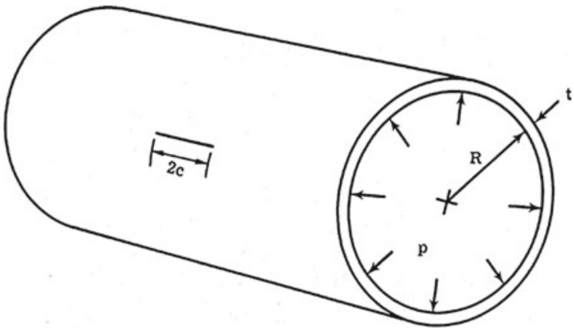

Fig. 8.1 Through-thickness crack of length 2c in a hollow cylinder subject to internal pressure. How does one experimentally test such a case?

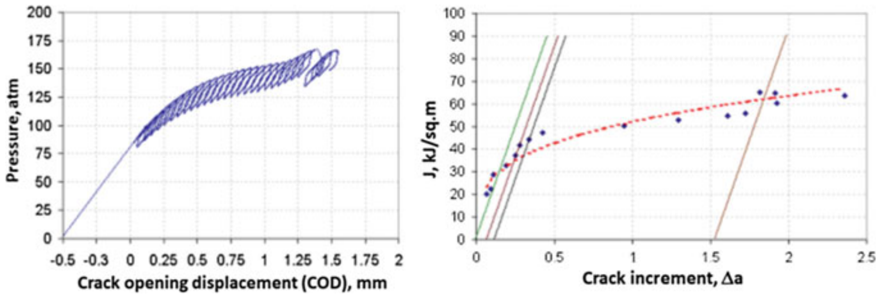

Fig. 8.2 (Left) Internal pressure versus COD and (Right) J versus crack growth increment registered during a test on a steel pipe with an 80 mm through-crack subject to internal pressure at 300 °C (Avinash et al. 2006)

- The cylinder needs also to be sealed at both ends. This must not induce any axial load on the specimen so as not to vitiate the required loading conditions.
- Provision should be made to enable measurement of crack opening displacement under varying internal pressure and increasing crack size.
- Finally, all the above testing arrangements need to sustain internal pressures to 250 atmospheres to permit loading to fracture. They also need to sustain a temperature of 300 °C to simulate actual service conditions.

Figure 8.2 shows typical readouts and results from the test rig at the time of its validation prior to shipment. These may well be the first published data of a successful J_{1c} test performed on a pressure vessel with a through-crack subject to internal pressure. Note the uncharacteristic loops during periodic *elastic* unloading. These loops are due to friction in the sealing arrangement over the through-crack. A procedure was devised to compute the actual compliance from the loop data in order to determine the crack growth increments, Delta CL.

Test results such as those in Fig. 8.2 assist the regulatory authorities in taking educated decisions regarding possible life extension of safety-critical components. The development of the associated test technology allowed the extension of a new standard testing practice to the case of a full-scale component. In doing so, available stress intensity solutions as well as numerically obtained compliance functions for a through-crack in a pressure vessel were experimentally validated, also for the first time.

For comparative purposes a test technology was developed at BISS to evaluate J_{1c} on miniature specimens (W = 8 mm).

These advances in test technologies have opened new avenues for research directed at the *multi-scale* comparison of mechanical properties such as fracture toughness and fatigue crack growth rates. Such comparisons are vital inputs for future designs as well as their validation and certification.

8.3 Recording Damage Growth in Static and Fatigue Testing of Carbon Fibre Reinforced Plastics (CFRPs)

For almost five decades a robust ‘business model built around Fracture Mechanics’ has been used in the design, evaluation and operation of safety-critical metallic structures. Standard practices using simple laboratory coupons are used for metallic material characterizations with respect to fatigue crack growth and fracture response. These property characterizations can be used to design for residual strength as well as for residual life in the presence of a crack. The latter, when combined with the capabilities of, and accessibility to, non-destructive inspection of the structures, ensure judicious planning of inspection schedules as an assurance of long-term safe and economical operation.

The track record of global civil aviation safety is testimony to the resounding success of this ‘business model’. A straightforward analysis of the operation of airliners would show that many of them do more miles *on the ground* in their lifetimes than most automobiles do in theirs! This is not to mention the tens of millions of miles ferrying passengers to their destinations. And the airliners do all this with an outstanding degree of both safety and economics of operation.

The introduction of high-strength lightweight Carbon Fibre Reinforced Plastics (CFRPs) as load-carrying, safety-critical structural elements has necessitated major changes with respect to the ‘business model’ that prevails for metals. Perhaps the most significant change is the requirement that composite structures be designed for ‘no growth’ of any damage, either pre-existing or introduced in service, e.g. impact damage caused by debris or tools. Although composites are *inherently* more resistant to fatigue damage than metals, the difficulty of predicting the residual strength of a damaged composite currently demands a more conservative ‘no growth’ approach, which can only be achieved by significantly reduced design stress levels and hence weight penalties.

The state-of-the-art in the application of composites damage kinetics to actual structures is more or less at the same level of competence as for metals in the early 1960s. The basic reason for this is that although computational techniques have advanced considerably in the intervening years, the wide variety of composite failure mechanisms, which depend not only on loading conditions but also the matrix and reinforcement fibre compositions and lay-ups, present a formidable problem.

A serious obstacle to the advancement of experimental research on composites is the absence of technology to register damage kinetics. For metals the fatigue and fracture testing is highly automated and requires little manual involvement to obtain the required data. On the other hand, BISS Labs experience with working on the Airbus A350 programme revealed that fatigue tests on composites at best yielded results in the form of stiffness variation with cycle count, while fracture test results came in the form of force versus displacement and/or strain gauge output. This was because reliable characterization of damage size and its growth demanded periodic specimen removal from the test rig for ultrasound scanning, with the specimen submerged in water. This laborious procedure was necessary because other available techniques like thermography and acoustic scanning are manual and subject to interpretation.

It was therefore desirable to develop a technique that could (i) operate without test interruption, (ii) be amenable to automation, and (iii) possess a degree of data processing that would allow fully automated testing for fatigue and fracture in much the same way as in laboratory testing of metallic specimens. Figure 8.3 describes the patented scheme developed at BISS for automated damage registration, and implemented as a standard supply on test systems for CFRP coupons. The system is built around an eddy current probe mounted on a 3-axis gantry that is hooked up to the controller for the entire test system. Software was developed for eddy current signal processing in order to periodically build up the image of the damage and compute its area. Specimen compliance data are also recorded. Thus, in an analogous way as for a metallic compact-tension specimen (where crack size can be plotted against cycle count or incremental load as in a J_{1c} test), it is possible to obtain a fully automated record of composite damage size versus cycle count or incremental stroke. Early tests indicate that this BISS-developed capability opens new avenues for research on the fatigue and fracture behaviour of CFRP laminates, namely the potential for data-intensive fatigue and fracture testing that may one day lead to improved design procedures for safety-critical composite structures.

Figure 8.4 shows some BISS-system test results for CFRP coupon damage growth against cycle counts. As one might expect, at lower applied stress levels the damage growth arrests after some time; but at higher stress levels the damage size can progress to failure. Interestingly, limited test data also indicated that fatigue cycling improves the residual tensile strength of impact damaged specimens. Such tests clearly suggest several interesting avenues for future work to address emerging questions:

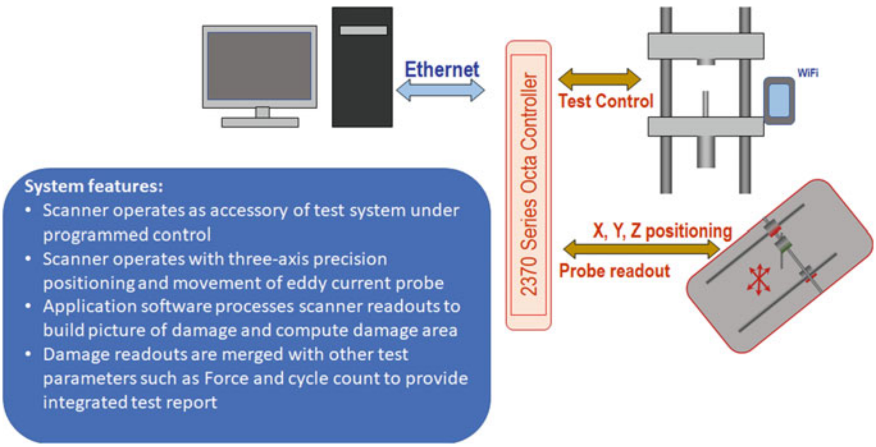

Fig. 8.3 Schematic of BISS test system integrated with scanner for tracking damage kinetics in CFRP laminate specimens during static and cyclic testing

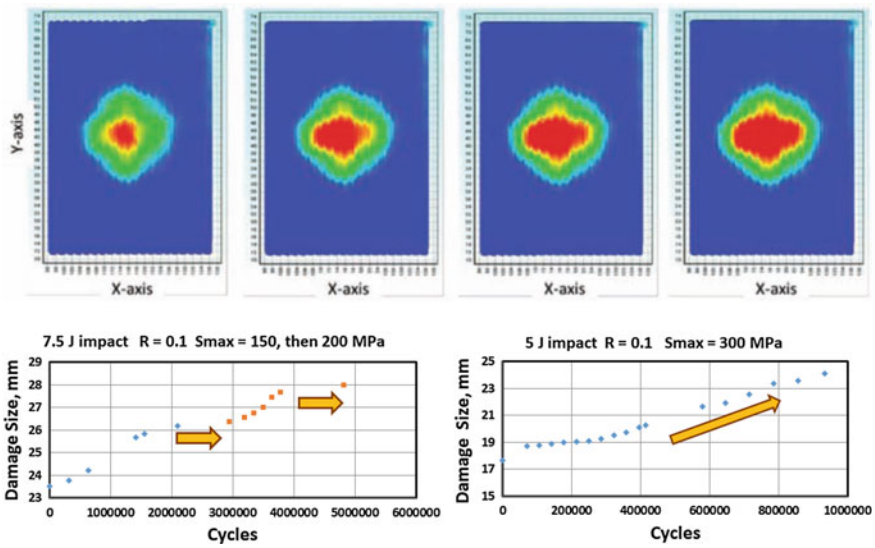

Fig. 8.4 Progressive fatigue damage growth recorded by BISS scanner on drop weight impacted CFRP coupons under cyclic loading (Top). Results from long duration fully automated testing under cyclic loading at 5 Hz (Bottom). At lower stress levels, damage arrests after some growth

- What is the compressive residual strength after fatigue cycling?
- What would be the effect of periodic compressive cycles, as in the case of the Ground-Air-Ground cycle for airframes?
- How will an impact damaged CFRP panel respond to static or cyclic biaxial loading as in the case of the pressurized fuselage?

These are but some of the problems that the new developments in test technology can address. In the longer term one might reasonably expect a paradigm shift in design approach, leading to highly stressed composite structures whose safe operation is assured through periodic inspections that are scheduled from the analyses of fatigue damage kinetics.

8.4 Unravelling the Science Behind the Residual Stress Effect in Metal Fatigue

The two examples cited in the previous sections of this chapter underscore the crucial role of developments in test technology in material property characterization of new or engineered materials. Described below is a research and development effort at BISS, over a period of ten years, that resulted in a path-breaking contribution to the understanding and analysis of metal fatigue. To place this result in proper perspective, it may be relevant to consider a concise summary of progress in fatigue analyses up to the 1990s.

8.4.1 First Concepts: S-N Curves and Linear Damage Accumulation (LDA)

A. Wöhler, the Superintendent of a Prussian Railway Depot in the mid-19th century, conducted fatigue experiments over a 17-year period (1852–1869), thereby laying the foundations for contemporary understanding of metal fatigue (Anon 1871; Wöhler 1870). Wöhler 'invented' the S-N curve that describes the relationship between applied stress amplitude and the number of cycles to failure. He also established the concept of a 'Fatigue Limit', the stress amplitude below which metals are unlikely to fail. Wöhler and Bauschinger, another pioneer, went on to establish the relationship between mean stress and fatigue limit, see Fig. 8.5 (Bauschinger 1886). They showed that the fatigue limit progressively diminishes with increasing mean stress. This is known as the mean stress effect (MSE).

Engineering application of Wöhler's findings required a procedure to account for the statistics of actual loading conditions, that, unlike those in Wöhler's experiments, are generally variable-amplitude. Some 60–70 years passed before Pålmgren, then Miner, proposed the concept of Linear Damage Accumulation (LDA) (Miner 1945). This concept provided a simple method of calculating the fatigue life from the 'damage sum' for any given mix of stress amplitudes representing service usage, whereby S-N curves were used to determine the damage fractions for individual amplitudes,

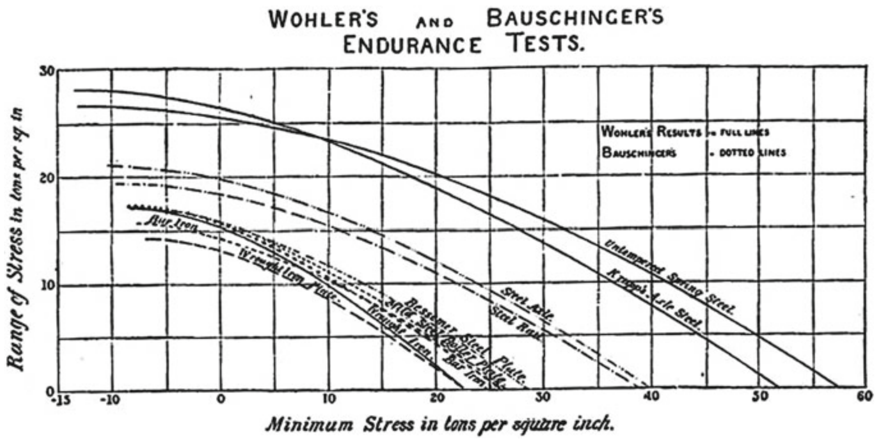

Fig. 8.5 Dependence of minimum (or mean) stress established by Wöhler and Bauschinger some 150 years ago (picture reproduced from Anon 1871)

namely as the ratio of cycle counts at each stress amplitude to the fatigue life at that amplitude. This simple concept was quickly discredited by programme-load experiments performed by Gassner in the 1930s (Gassner 1939). Gassner showed that the damage sum at failure could vary greatly and unpredictably from unity, depending on the load history (fatigue spectrum) and also, the material. Nevertheless, the LDA concept has been widely applied to engineering structures and is still remarkably popular to the present day.

8.4.2 Notched Fatigue, Mean Stress, LDA, and Local Stress-Strain (LSS)

Most fatigue failures occur at notches. When the applied stress multiplied by the *elastic* stress concentration factor, K_t, exceeds the yield stress, the notch root will see inelastic response. Given that stress-strain hysteresis occurs, the notch root mean stress will not only be different from the applied mean stress, but also become load sequence dependent, as illustrated in Fig. 8.6.

This raised the possibility that provided one could compute the actual notch root mean stress for individual cycles of a given load sequence, then maybe the LDA

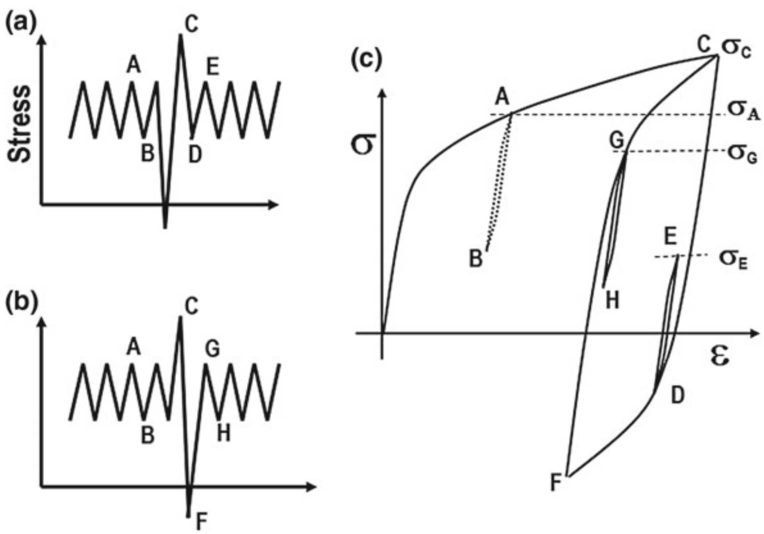

Fig. 8.6 Notch root mean stress sensitivity to load history. Load sequences (**a**) and (**b**) are equivalent, but the overload cycle's peak and valley are interchanged. This causes a dramatic change in local mean stress at the fatigue notch root as seen in (**c**) (GH vs. DE). This effect is modelled in engineering notch fatigue analysis to account for the effect of load history on fatigue life. The effect ought to vanish under fully elastic response. But in reality it actually gets more accentuated! Research at BISS was able to explain why this may be so

concept would enable realistic estimates of notch fatigue life. Indeed, the Local Stress Strain (LSS) approach that performs such modelling has served industrial design for over 40 years. However, the LSS approach fails *the very basic test of fully-elastic notch root response*. This problem is important, because designers try to keep local stresses elastic: but in this case the local mean stress would be rendered insensitive to the load sequence!

In practice, the *opposite* is true—as the overall stress levels reduce the load sequence sensitivity *actually increases*. This should not come entirely as a surprise because mean stress sensitivity increases with decreasing stress/strain amplitude. Manson noted as recently as in 1987 that "a meaningful rationale for the mean-stress effect would be a noteworthy achievement over the coming 25 years". Manson's expectation, which was expressed in the lead paper presented at an ASTM Annual Symposium (Manson 1988), underscored the limitations of the empirical correlational approach that had prevailed for over a century.

At BISS we decided that the key to understanding variable-amplitude fatigue is to determine exactly how and why mean stress affects the process of *early fatigue crack growth*, viz. at stress amplitudes close to the fatigue limit. This demanded the development of application software to apply user-programmable load sequences, do so with scrupulous adherence to the required peak-valley sequence in loading and with high precision using suitable adaptive control techniques. Later, the control techniques were fine tuned to accelerate testing for threshold conditions through high precision loading at frequencies as high as 150 Hz, permitting application of a million load cycles in three hours. As will be shown below, these led to a new understanding of how mean or residual stress affect fatigue thresholds. In atmospheric fatigue, the dominating parameter is the stress at the crack tip at the commencement of the rising half of the fatigue load cycle. This parameter controls diffusion kinetics of active species into crack-tip surface layers and affects their resistance to micro-fracture. Unlike notch root response, crack-tip cyclic stress-strain response will always be inelastic and therefore sensitive to load history, even if applied or notch root stresses remain elastic.

8.4.3 Load History Effects on Fatigue Crack Growth (FCG)

Unlike cumulative damage, crack sizes and their growth can be measured. High resolution scanning electron microscopes (SEMs) made it possible to track even extremely small cracks. BISS control units allow the application of periodic 'marker loads' that leave behind discernible progression markers of microscopic crack extension on the fracture surfaces. These progression markers enable quantifying load interaction effects in a highly reproducible manner, even in cases where classic fatigue striations do not occur. This quantitative fractography (QF) capability was used to unravel the underlying science behind the mean stress effect, by (i) considering whether and how the available FCG load-interaction models could explain the QF results, and (ii) exploring the possibility of alternative explanations.

The three most popular load-interaction models were scrutinized for validity under controlled test conditions. One was the crack closure mechanism and model proposed by Elber (1971). The other two were the residual stress models proposed by Wheeler (1972) and Willenborg et al. (1971). Elber demonstrated that a fatigue crack can be partially closed during a tensile load cycle. He came up with the concept of an effective stress intensity range, ΔK_{eff}, that can be less than the applied ΔK. The ratio $U = \Delta K_{eff}/\Delta K$ was shown to increase steadily with applied stress ratio, i.e. increasing mean stress. Since the crack wake formation and response is by definition sensitive to load history, the crack closure mechanism might be expected to explain load history effects.

The Wheeler and Willenborg models are based on the premise that a tensile overload will leave behind a zone of compressive residual stress within the monotonic plastic zone, and that this residual stress zone will retard subsequent crack growth. This is actually an extension of the MSE.

8.4.4 Discovery of the Science Behind the Mean Stress Effect (MSE)

First experiment: This involved the repeated application of a three-step programmed load sequence (Sunder et al. 2002). All three steps were of identical low amplitude and equal duration (3000 cycles), but slightly shifted in terms of mean stress, and also separated by marker loads. The stress ratios of the three-step load sequences were kept high to eliminate any effect of crack closure; and the marker loads carried a low minimum level, in order to periodically 'squeeze' the crack wake and keep the crack fully open. The goal was to determine whether there was any effect of mean stress on crack growth during the separated periods of low amplitude cycling.

Figure 8.7 shows some highly significant (and rather serendipitous) near-threshold FCG fractographs from this first experiment:

(1) In Fig. 8.7a the differences in the marker load spacings reveal a noticeable MSE during early crack growth. However, on the same fracture surface (well beyond the extent of Fig. 8.7a) it was obvious that with increasing crack size and hence growth rate the MSE became negligible, indicating a fully-open crack (Sunder et al. 2003):

- From a crack closure standpoint, these results cannot be explained, particularly since, at the point of FCG nucleation there can be no crack wake to cause closure. If one were to insist on closure being the reason for the different marker load spacings during early FCG, then one would also need to explain why adjacent spacings later became similar.
- These results also cannot be explained by either the Wheeler or Willenborg models. Neither distinguishes between FCG behaviour at low and high growth rates. More specifically, these models cannot explain why there is an MSE at low growth rates but not at higher growth rates.

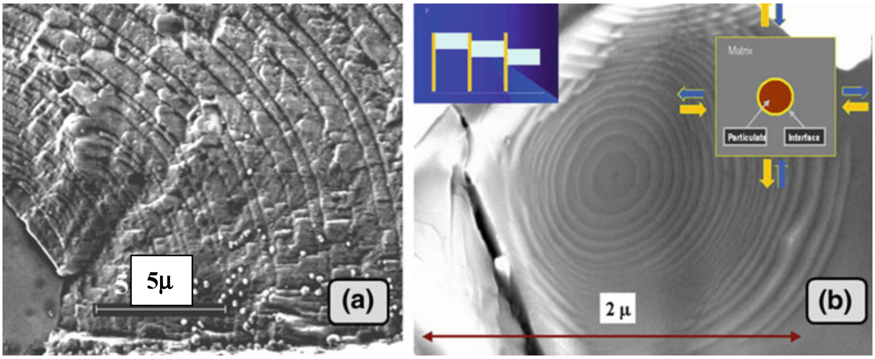

Fig. 8.7 **a** Growth of a naturally-initiated fatigue crack from a secondary particle (inclusion) on the notch surface of an Al-Cu alloy specimen (Sunder et al. 2002). The effect of mean stress and/or load history is obvious from the initially large differences in crack growth increments between steps. These differences steadily diminished with increasing growth rate, and all three steps eventually showed identical crack extension. **b** Interfacial cracking separating a secondary particle from the matrix, and seen on the same fatigue fracture surface (Sunder et al. 2002). The separation must have occurred ahead of the main crack tip **and therefore in high vacuum**. Note the identical crack increments between programmed markers after each step: this is despite the mean stress variation for each step, and contrasts with the early crack growth in (**a**)

(2) The clue to this conundrum came by way of Fig. 8.7b. As stated in the figure caption, this fractograph shows interfacial crack growth separating a secondary particle from the matrix. This remarkable evidence was found at a very small crack size and at extremely low FCG rate less than 10^{-8} mm/cycle. At first glance, this fractograph would seem contradictory, since adjacent marker load spacings are the same, unlike the situation depicted in Fig. 8.7a.

However, there is a fundamental difference between the two cases: in Fig. 8.7a the FCG was in air; but in Fig. 8.7b the crack growth occurred *in high vacuum (less than 10^{-8} torr)*, since interfacial cracking leading to separation of the particle from the matrix by fatigue requires a local triaxial stress state, and this is possible only when the point in question is ahead of the main crack tip, i.e. in the interior of the material.

From the foregoing observations, it would follow that the existence of an MSE might be an environmental effect. On the other hand, one could argue that interfacial cracking around secondary particles cannot be readily compared with the main surface crack. Verification of the environmental possibility required actual testing of the same test specimen alternately in air and high vacuum under repeated blocks of three-step loading.

Second and third experiments: Two follow-up experiments were performed at the Air Force Research Laboratory (AFRL, WPAFB, OH, USA) on a high vacuum test system capable of 10^{-8} torr and with a BISS test system controller to generate the required command waveform. The first experiment was on an Al-Cu alloy (Sunder et al. 2003), the second on a nickel-base superalloy at elevated temperature (Ashbaugh et al. 2002). In both cases cycling was continued to failure with periodic switches of the environment from air to high vacuum and back. Each experiment took a month, since each switch from air to high vacuum required two days.

Both experiments confirmed that the near-tip MSE involves environmental action. In high vacuum, the crack growth rate in both experiments was identical in multiple steps applied at different mean stress. The fact that the change in environment from air to vacuum and back to air caused instantaneous changes in crack growth response suggested, that the effect has nothing to do with crack closure, and may in fact be attributed to the weakening by embrittlement of near-tip surface layers by active species in the environment, with instantaneous near-tip residual stress moderating the extent of diffusion-induced weakening of crack-tip surface material.

8.4.5 The Brittle Micro-Fracture (BMF) Theory

The results from the second and third experiments provided the basis for the theory of brittle micro-fracture (BMF) (Sunder 2005), whereby the fracture strength of the crack tip surface layers is affected by near-tip residual stress that, in turn, is load sequence sensitive. It has long been known that surface diffusion of hydrogen released by oxide/hydroxide formation can affect the FCG rate (Petit et al. 1372); and perhaps this process is also responsible for striation formation (Bowles 1978). What our research showed was that near-tip residual stress moderates the crack-tip surface diffusion kinetics, such that the crack-tip surface layers vary in their resistance to BMF, thereby inducing the mean stress (near-tip residual stress) effect. Since only surface atomic layers are affected, the crack-tip surface layer effect (and hence the near-tip MSE) decreases with increasing growth rate.

In other words, our second and third experiments essentially demonstrated that whilst mechanisms such as closure affect the mechanics (driving force) of fatigue, near-tip mean stress affects the material's resistance to environmental FCG. This result is explained by the BMF theory.

An important corollary of the BMF theory relates to the consequence of near-tip hysteretic cyclic stress-strain response. As is seen from Fig. 8.6, hysteretic response makes load interactions cycle-sequence sensitive, even if there is no crack extension. Thus hysteretic-response-induced changes of the near-tip mean stress can by themselves change the cycle-by-cycle resistance to BMF. In contrast, crack closure cannot exhibit cycle sequence sensitivity because the crack wake can yield only in compression. This was shown by a fourth experiment, discussed next.

Fourth experiment: Steps of extremely small load amplitudes superimposed on the rising and falling halves of periodic overloads highlighted the hysteretic nature of variable-amplitude near-threshold fatigue crack growth, with cycle sequence sensitive FCG rates varying by over an order of magnitude (Sunder 2005). This carefully engineered experiment, backed by BISS test control software, confirmed the possibility of extreme crack growth retardation in the total absence of crack closure. It also showed that the effect becomes negligible as the FCG rate increases into the Paris Regime, where crack extension is predominantly driven by shear and the surface diffusion sensitive contribution is restricted to the depth of crack-tip atomic surface layers.

Fifth experiment: The mean stress (near-tip residual stress) effect and crack closure are two independent load interaction mechanisms. The former diminishes crack-tip surface resistance to fracture at the next load excursion. The latter moderates the mechanics of crack tip stress-strain response. A multilevel programmed load sequence was specially designed to demonstrate how these two entirely different phenomena combine to cause load interaction effects. The experiment was specially designed to induce load interaction under different degrees of crack closure, ranging from a fully open to a fully closed crack, combined with near-tip residual stress ranging from compressive to tensile. Quantitative fractography of fatigue crack extension under six different combinations of the two effects served as further validation of the BMF theory (Sunder 2005).

8.4.6 Significance of the Experiments for Near-Threshold FCG and ΔK_{th} Determination

In general, the linear-elastic fracture mechanics (LEFM) parameter ΔK, or its correction for closure in the form of ΔK_{eff}, has been treated as the sole correlating parameter for FCG rates for a given environment. However, BISS in-house and supported research established that ΔK_{eff} cannot serve as a unique correlating parameter under near-threshold variable amplitude loading. The current ASTM Standard E647 for determining near-threshold FCG and ΔK_{th} prescribes a load-shedding testing technique, using blocks of constant amplitude loading, that effectively guarantees the reproducibility of the same near-tip residual stress. However, under variable amplitude loading this near-tip residual stress will vary widely, and this implies that ΔK_{th} can undergo a cycle-by-cycle variation. This possibility has not been recognized until our experiments were done. It follows that ΔK_{th} values and near-threshold FCG rates obtained via ASTM E647 may not be appropriate for engineering estimates of residual crack propagation life under service loading. To extend the ASTM E647 procedure to variable amplitude service load histories it is necessary to establish the relationship between ΔK_{th} and near-tip residual stress. This has been the objective of a two-pronged research and development effort launched at BISS (Sunder 2015), involving (i) an analytical effort to model near-tip residual stress as a function of load history, requiring new equations and an algorithm, and (ii) a new experimental procedure to estimate ΔK_{th} under controlled conditions of near-tip residual stress.

BISS developed a suitable test technology to facilitate and accelerate the determination of ΔK_{th} as a function of near-tip residual stress. The equipment permits precision cyclic loading at up to 200 Hz, interspersed with accurately applied overload-underload sequences in order to reproduce an entire range of desired residual near-tip

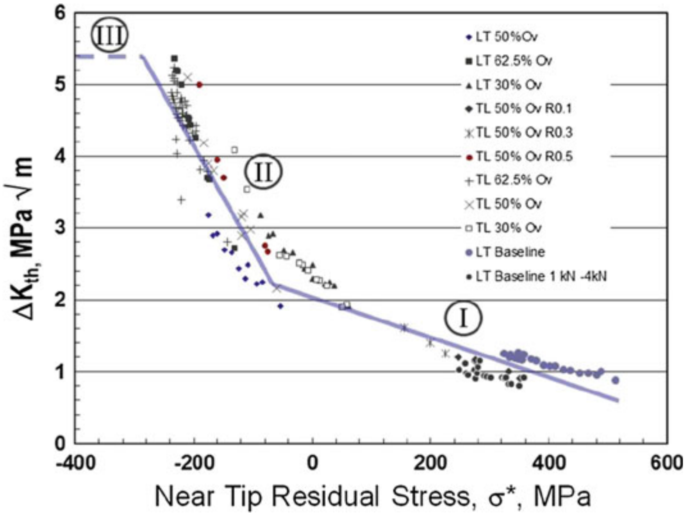

Fig. 8.8 Relationship between ΔK_{th} and near-tip residual stress for 2024-T3 Al-Cu alloy specimens with LT and TL orientations (Sunder 2015). These tests were performed by Kiran Kumar from Manipal Institute of Technology as part of his Masters Thesis. Each point corresponds to no-growth conditions under highly controlled near-tip residual stress induced by overload/underload sequences. **N.B**: Wöhler and Bauschinger obtained similar looking curves some 150 years ago for the fatigue limit, which is an analogous parameter!

residual stresses. Test equipment incorporating this capability has since been supplied to several overseas customers. These developments were combined with a research programme that made it possible to establish the relationship between ΔK_{th} and a certain history sensitive near-tip residual stress, see Fig. 8.8 (Sunder 2015).

The relationship in Fig. 8.8 has three segments. The shallow slope of Segment I indicates a relatively slight effect of near-tip residual stress on ΔK_{th}. Data obtained under constant amplitude loading or by controlled load-shedding (as under ASTM E647) would fall in this segment, possibly towards its right end. However, as the near-tip residual stress goes into compression, in Segment II, the value of ΔK_{th} steeply increases *almost five-fold* in comparison to what would be obtained from the prevailing standard practice. This beneficial effect of compressive stress, i.e. much higher ΔK_{th} values, plateaus into a hypothetical Segment III, for two reasons: (i) it becomes difficult to drive down residual stress any further, and (ii) the physics behind the process control the result—one cannot drive diffusion kinetics below zero, which is the situation *in vacuo*. (In fact, the available fractographic evidence does suggest that there would be a near-flat Segment III in high vacuum.)

8.5 New Avenues for Research

Thanks to advancements in test techniques in conjunction with the capability of high resolution scanning electron microscopy and quantitative fractography, a complete transformation has occurred in understanding the nature of the MSE in environmental (atmospheric) metal fatigue and crack growth. We are finally in a position to explain what was established some 150 years ago. This understanding will help to plan and execute new experiments to characterize the finer aspects of load interactions in fatigue. These will contribute to building the foundation for future analytical modelling, of fatigue durability and residual life under service load spectra. Two recent examples are noteworthy and are mentioned in the next paragraph.

Test systems equipped with the required application software and instrumentation to perform FCG near-threshold variable amplitude tests under highly controlled near-crack–tip residual stresses were installed at the Volgograd State Technical University (VSTU) and the Tomsk Polytechnical University (TPU) in the Russian Federation. Collaborative experiments under new, specially designed load sequences were set up with colleagues at VSTU and TPU (Sunder et al. 2016a, b). These tests demonstrated, via crack arrest, the dramatic effect of compressive near-tip residual stress in instantaneously pushing ΔK_{th} beyond ΔK_{eff}. The tests also (i) demonstrated that overload-underload re-sequencing affects ΔK_{th}, and not crack closure as was hitherto believed, (ii) confirmed previous findings of crack-tip blunting momentarily removing closure altogether, and (iii) demonstrated for cracks with well-developed wakes that closure recovery after blunting by overloads occurs very rapidly, within about 1% traversal of the monotonic plastic zone. Such details are bound to benefit the cause of realistic modelling.

Considering that the effects of mean stress and residual stress on metal fatigue are universal, one may expect that relationships similar to the one in Fig. 8.8 will exist for all metallic materials subject to environmental (atmospheric) fatigue. Work is in progress to develop a multi-mechanism analytical model for estimates of spectrum load crack growth based on cycle-by-cycle calculations of ΔK_{th} as well as crack closure. This approach is based on the new understanding that while ΔK_{th} characterizes history-sensitive variations in material resistance to (near-threshold) crack extension, crack closure reflects history-sensitive variations in crack driving force. Crack-tip blunting serves to momentarily reduce or remove closure, but cannot affect the near-tip residual stress and its associated ΔK_{th}.

8.6 Concluding Remarks

As BISS celebrates its Silver Jubilee, an opportunity arose, in the form of this chapter, to summarise major scientific and technical contributions from an Indian start-up. Three examples of the research and development effort at BISS deserve particular mention. All three are unique, in that no previous mention of similar efforts can be found in the open literature:

1. A test technique and procedure were developed to determine J_{1c} on a pressure vessel with a through-thickness crack. This procedure included sealing arrangements to withstand high pressure and temperature but not inhibit crack opening, compliance and growth; and instrumentation to monitor the crack size, perform pre-cracking with load shedding, and follow up with testing under incremental COD control to estimate stable crack extension from compliance measurements under periodic unloading. This development was extended to irradiated piping holding nuclear fuel elements, and has been implemented for ageing nuclear power reactor components to confirm their structural integrity.
2. A damage scanner for CFRP laminates was developed and integrated with the test system to enable fully automated tracking of damage growth during static and cyclic testing. This permits study of damage kinetics in CFRP specimens as a function of applied loading, and is likely to assist in the development of new understanding and analytical models to model the residual lives of CFRP structural elements.
3. Innovative research backed up by specially designed test procedures that are not possible with conventional 'black box' test systems helped unravel the science behind the residual (mean) stress effect on fatigue limit and near-threshold fatigue crack growth. Results of specially targeted experiments underscore the importance of near-tip hysteretic stress-strain response in controlling the instantaneous threshold resistance to fatigue crack growth. Subsequent research resulted in the development of an analytical model relating applied load history to near-crack-tip residual stress. Thanks to this effort, a relationship was established between near-tip residual stress and the corresponding instantaneous ΔK_{th}.

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Chapter 9
Lightweighting—Systematic Approach in Aerospace Industry

A. S. Kiran Kumar

9.1 Introduction

From the time of the Wright brothers, it has always been the constant endeavour of aerospace designers to push the limits to achieve greater efficiency and higher payload capability at a reasonable cost. The field of aerospace has witnessed continual innovation in the materials, propulsion, control systems, structures, safety design and electronics, with their spin-offs benefiting other domains of science and technology, as well. As you all know, materials are fundamental to the progress in this area and the constant R & D in this area has helped the world to evolve towards lightweight, high strength, corrosion resistant, durable and survivable metals, alloys and composites, along with the associated manufacturing processes. This assumes significance in the face of the fact that the aerospace industry in our country is poised for a phase of accelerated growth under the Government's Make-in-India strategy and a focused effort in acquiring self-reliance in aerospace materials and capacity building within the country to support this growth is vital.

The term "lightweighting" would imply the mere substitution of existing materials with their lightweight substitutes to achieve the desired payload efficiency; but experienced aircraft, launch vehicle and spacecraft designers would look beyond such a narrow perspective and opt for a systems approach to perform lightweighting at the systems level to ensure proper balance with all other critical requirements. The benefits accrued through lightweighting in optimizing vehicle performance, capability, fuel consumption and costs are unanimously accepted in the design community and fully justify the investment of funds, time and effort to progress towards multifunctional and lightweight materials with reliable and optimum Manufacturing processes.

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The harsh and unforgiving environment of space introduces further challenges to such materials since they have to ensure the same attributes including the adaptability and survivability of space vehicles during atmospheric ascent and descent, deep space or other planetary atmospheres.

9.2 Lightweighting—An ISRO Perspective

ISRO has been continuously striving towards achieving these benefits through alternate materials, optimized design and manufacturing processes in its launch vehicle and spacecraft programmes. PSLV was the first operational launch vehicle that established indigenous capability to launch spacecraft from Indian soil and has matured into a workhorse vehicle that can launch multiple satellites into multiple orbits. The first satellite that was successfully injected by PSLV into the sun synchronous polar orbit 1993, IRS-P2, weighed 804 kg. Today, its payload capability into that same orbit has been systematically enhanced to 1750 kg through a series of improvements including lightweighting, alternate materials, increased propulsion efficiency, optimal mission design, reconfiguration of avionics and better manufacturing processes. In the four stage PSLV rocket, the payload sensitivity of the stages starting from the first stage, is 1:60, 1:1 0, 1:2.5 and 1:1 respectively. This means that every 60 kg saving in the first stage of PSLV contributes 1 kg to the payload capability while every reduction in the mass of the fourth stage directly contributes to the payload capability. Similarly, the GSLV lofted its first satellite weighing 1500 kg in 2001 while the previous flight launched 2230 kg into the Geosynchronous transfer orbit. This enhancement in the PSLV/GSLV payload capability can be attributed to the various lightweighting strategies adopted in the choice of materials, manufacturing processes and system design.

9.3 Materials

ISRO took up the challenge of developing various materials in its very early phase of inception through extensive technology development programmes, that has ensured self-reliance in critical space materials. However, realisation of various materials meeting stringent quality norms was a formidable task considering the complete lack of experience of Indian industries in this sector until then. The development of Maraging steel during the 1980's has been a notable achievement in the country under the leadership of luminaries such as Dr. Brahm Prakash, which has been the main constituent of the motor cases for the solid boosters. This was followed by a focused national programme for the indigenization of Aluminium alloys along with indigenous capacity development in the realisation of alloys of Titanium, Copper, Magnesium etc and super alloys for the space programme. Lightweighting through composite structures has been followed as a concurrent strategy in achieving the desired mass savings because of their superior mechanical properties like high strength, stiffness combined with low density and multi-directional properties.

The first flight of GSLV used a metallic payload adapter for mounting the spacecraft. The subsequent flights switched to a composite adapter that resulted in significant mass saving (30 kg), which directly contributes to the payload capability. The initial configuration was made out of closely stiffened shell metallic structure, that has been replaced with a composite sandwich construction, which was preceded by thorough structural and systems analysis before induction. The other major structure which has benefited by a composite structure is the payload fairing or heat shield, especially in the 4rn payload fairing of ISRO's new launch vehicle, GSLV Mk-III. From the outset, GSLV Mk-III adopted a CFRP payload fairing, which is a major boost to its payload capability. A CFRP version of the GSLV payload fairing has been qualified and indicates a mass saving of almost 400 kg. The challenge here is to sandwich an aluminum honeycomb structure within a composite shell for realizing this large composite structure which has the necessary stiffness and strength to protect the payload during the harsh atmospheric flight of the launch vehicle.

The initial flights of PSLV used an aluminum alloy structure for the inter-stage between the third and fourth stages. This was replaced by a composite structure consisting of a stiffened shell construction and tubular members. The aforementioned systems approach was employed during the design of this structure in order to eliminate the usage of rivets for joining the stiffener to shell, which greatly reduced the realisation cycle along with the associated mass savings.

Four numbers of high pressure titanium alloy gas bottles are used in the pressure-fed liquid propulsion system in the fourth stage of PSLV. The Mars Orbiter Mission called for the maximal payload capability of the PSLV and this was one of the areas that provided the required optimization through the adoption of Carbon-epoxy wound titanium gas bottles. The carbon-epoxy wound titanium gas bottle offers higher mass efficiency, high specific strength and better strain compatibility and composite properties. This also called for specific manufacturing processes and is now available as an option in PSLV missions, where the payload margins are very less.

The lightweighting strategies in the Indian Cryogenic Upper stages for GSIN and GSLV Mk-III were particularly challenging considering the use of cryogenic fluids and specific material requirements. For instance, development of the titanium gas bottle (Titanium alpha alloy: Ti5Al2.5Sn-ELI) required for the cryogenic stage was a major challenge for the first developmental flight of GSLV MKIII. Since these gas bottles are directly mounted inside the liquid hydrogen tank, it experiences temperatures as low as 20 K. The major challenge was to limit the hydrogen concentration in the material to avoid hydrogen embrittlement. This risk would have been avoided if the gas bottles of compatible material were accommodated in the liquid oxygen tank but this would have required 5 bottles compared to the 2 bottles in the liquid hydrogen tank. This option would mean a major weight penalty of 60 kg. Key improvements in the fabrication processes, welding and decontamination for limiting the hydrogen concentration were implemented and the gas bottles were successfully realised, tested and flown in the first developmental flight of GSLV Mk-III.

The insertion of lightweight materials especially composites into the structural elements has been a constant strategy adopted in ISRO's satellites since the beginning, where a high precision composite antenna reflector was used in APPLE—India's first communication satellite. Composite antenna reflectors are excellent examples of the use of multifunctional materials combining the advantages of lightweight, specific stiffness, tailorability and RF reflection efficiency, which should be capable of withstanding the deep space environment for the lifetime of the satellite. High modulus carbon fibre epoxy composites with metallization are most suitable for such applications. The capability of fabricating lightweight antenna reflectors for different generations of ISRO's satellites has evolved ranging from 2 m deployable shaped reflectors, 2.2 m deployable Dual gridded reflectors to 6 m unfurlable antennas.

9.4 Manufacturing

Lightweighting imposes manufacturing challenges and require improvements in joining and welding technology, parts consolidation, miniaturization, testing and qualification. The future ISRO programmes such as the winged-body RLV employed non-conventional manufacturing processes to realize integrated stiffened structures and thermal protection systems. In RLV-TD, the top and bottom panels for the wings, side panels and bottom panels for the fuselage are made out of integrally machined and stiffened structures. Compared to the conventional riveted built-up sheet metal structures, integrally stiffened machined structures require significantly less number of parts, machining, assembly time and cost. Such structures were realized through the development of a high speed machining process, which provides advantages such as increase in productivity, better surface finish, ability to machine high aspect ratio thin walled structures, etc. mainly due to the higher cutting speeds and consequently low cutting forces.

The Space borne Optical Telescopes generally used in satellites for cartographic applications have mirrors that are typically made of glass or glass-ceramics which have extremely low coefficient of thermal expansion. In order to have high resolution imagery, these telescopes are made with very large apertures which mean the mirrors used in them have large diameters. These mirrors are light weighted by removing material selectively in the form of a pattern, such as an isogrid structure, with equilateral triangular shaped pockets made in the back side of the mirror, with certain modifications to accommodate mirror mounts, which drastically reduces the weight without reducing the stiffness. Typically, lightweighting in the range of 62—85% have been achieved for these mirrors. Diamond impregnated tools are used for machining the pattern as the substrate material is glass-ceramic which is very hard to machine with conventional tools.

Advanced processing methods must often go hand-in-hand with the development of advanced materials used for Lightweighting. The final design will be improved only through a systems approach that jointly addresses the fundamental material development, advanced processing and design, which allows us to have a clear visibility of the trade-offs.

9.5 System Engineering and Reconfiguration

Reconfiguration of some of the structures have also brought about significant mass savings in the launch vehicles. The liquid oxygen tank in the GSLV Cryogenic Upper Stage has a concavity at the aft end, which was initially realised as a monocoque conical structure. Reconfiguration of this conical structure as an iso-grid design resulted in substantial mass savings in the upper stage of GSLV with the associated payload advantage. The related structural reconfiguration did not require any additional infrastructure at the industry. In PSLV, the dual launch adaptor is an important composite structure enabling the launch of multiple satellites. This structure was reconfigured from a composite sandwich construction to a gridded construction, which resulted in significant cost as well as mass savings. This was achieved through precise structural engineering by a combination of the natural strength of the material, simple beam elements and efficient joints for load transfer.

Current communication satellites of ISRO employ Chemical Propulsion System (CPS) for the orbit raising, station keeping and orbit control manoeuvres. ISRO has undertaken the development of high thrust 300 milli-Newton (mN) Electric Propulsion System which can perform these operations, towards the realisation of an All-Electric Communication Satellite, thereby completely replacing the Chemical Propulsion System. The use of electric propulsion results in a reduction of the satellite mass by about 35–40%. This would eventually facilitate the launch of heavier satellites onboard the indigenous launch vehicles. Lower thrust electric thrusters have been flight tested for station keeping operations in the recently launched South Asia Satellite.

The early Navigation Guidance and Control system in ISRO's launch vehicles were based on a distributed computer architecture with point to point serial communication links interconnecting the various modules. Increasing complexities in computational requirements, as well as in inter-module data transfer called for an improved architecture. Thus a computer system using a high performance microprocessor was developed, with a standard Avionics data bus architecture being used for inter-module communication. This new architecture resulted in improved reliability, lower power consumption and considerable savings in weight, while offering higher performance in computing speed.

9.6 Lightweighting—The Road Ahead

Several strategies are being explored in the area of materials, manufacturing processes and system configurations to achieve payload gain in future ISRO programmes. The fabrication of the large solid motor cases through flow forming is being viewed with great interest, considering the elimination of joints, efficient use of material and significant cost and time reduction. Composite motor cases and propellant tanks are other possibilities being explored. Reliable joining/welding technologies such as friction stir welding are being attempted in the propellant tanks for future launches. The avionics systems are getting miniaturized in future launch vehicle configurations to achieve more weight savings. Parts that are manufactured through additive manufacturing or 3D-printing have started getting adopted in aerospace systems worldwide including our programmes. For instance, the advanced GSAT-19 communication satellite launched by the GSLV Mk-III in June 2017 carried a 3D-printed Ku-band NW Feed Cluster. The realisation of Mirror Fixation Devices in the satellites made of Invar through additive manufacturing using the Direct Metal Laser Sintering process have proved to be fast, flexible and cost-effective without loss of performance compared to the conventional machining process.

9.7 Conclusions

Materials research to identify potentially useful metallic alloys and composites is highly involved and more often than not the development time for new, lightweight and multifunctional materials exceeds the development time of the aircraft, launch vehicle or spacecraft. This is because material development involves the sequential synthesis of the material and extensive testing of many properties and combinations in order to have a good understanding of the material's response and failure mechanisms. The complexity of material development is evident by the fact that the improvement of one property often causes degradation of another, which makes material design a compromise or trade-off. Thus, if we attempt to make a product stronger by making it thicker, it also gets heavier. If we use better materials, the cost increases. New material development must always be far ahead and should be moving towards maturity to achieve the capabilities foreseen in the future aerospace programmes. The long development timelines necessitate computational tools for the design of materials and better understand their behavior and design better structures. The availability of accurate, comprehensive design and analysis tools to realise the full potential of lightweighting of structures is a major challenge. As mentioned before, a systems approach of integrating lightweighting strategies into the engineering of new systems at the outset can go a long way in achieving the full potential of such strategies.