High-Temperature Materials for Gas Turbine Applications

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Contents

Foreword

Gas turbine is one of the most highly complex engineering systems built so far and is surely a great example of human endeavour. Operating in a very harsh environment with temperatures nearing or exceeding the melting point of the known materials, gas turbines need to function efficiently with a high degree of reliability, especially in an aircraft application. Designers have solved many problems innovatively with proper thermal management, selection of appropriate materials, and perfecting the design and manufacturing processes.

Gas turbine is a unique product that needs the application of basic sciences, an understanding of the design intricacies, and selection of proper material and manufacturing processes. Though the book is focused on material for gas turbines, Debashis Mukherji dealt with the subject comprehensively starting with the historical perspective of using metals for the development of artifacts, basic thermodynamics, and design features. Material for gas turbines is presented systematically through several chapters and finally, two major groups of material – Ti alloy and Ni-based superalloys have been presented in greater detail. New areas of material research are briefly presented. Both students and practitioners of the gas turbine will find this book not only highly interesting and informative but also a good guide for the design and development of gas turbines.

15 March 2023

Mr Amal Kumar Chakrabarti
ex-Director DRDL
Hyderabad

Preface

Gas turbines that are used for aerospace or land-based applications are one of the most complex devices developed by the humans. A single jet engine in the aircraft can have 10 to 15 thousand parts. Not only that, but the components in the gas turbine are also subjected to high temperature and pressure that vary in the different sections of the engine (compressor, combustor, turbine, etc). Thus, a variety of materials are needed to build these complex machines. The rotating components, especially the turbine blades are one of the most severely loaded high temperature components in any man-made machines, in which the gas temperature (in excess of 1500 °C) exceeds the melting temperatures of the metallic alloys used for the blades.

In addition, the high velocity gas flowing through the engine are extremely erosive, corrosive, and oxidising in nature, therefore, many components, particularly in the turbine and combustor, need special protection. To meet these design challenges, a wide range of high-performance materials are needed to construct the gas turbines. Many of them are metallic materials, like the high-strength steels, light weight high specific strength titanium alloys and heat resistant Ni-base superalloys. Other material groups like ceramics, ceramic- or metal-matrix composites and intermetallic alloys are becoming more relevant and they are replacing metallic alloys in advanced gas turbine engines, since they provide very high specific strength and enhance engine performance. Moreover, many critical components need advanced processing techniques and are protected with corrosion and thermal barrier coatings.

The monograph discusses a variety of high temperature materials (with emphasis on Ti-alloys and Ni-superalloys) that are used in gas turbines and compiles technical information on them, thus it is essentially a book on material science. However, due to the complexity of the gas turbines and their wider appeal, the materials used to construct them are of equal interest for both the material scientists and the mechanical/aeronautical engineers. I realised that to satisfy both these communities the monograph should have a wider base, so that the material scientists can understand the requirements of gas turbines and the engineers and the designers are exposed to some fundamental aspects of the materials used. Thus, the monograph first discusses some fundamentals of gas turbines and how it was developed on a historical perspective, before concentrating on the various materials and their development.

The monograph begins with a historical perspective in Chapter 1, and first discusses how discovery of early metals changed human development and then discusses the development of gas turbines. Starting with historical windmills and water wheels it describes chronologically the development of turbines for hydropower, eventually culminating in steam and gas turbines of today (continuing into Chapter 2). In Chapter 2, the theoretical design aspects relating to thermodynamics of gas turbine cycles are discussed as well. The various components of the gas turbine: compressor, combustor, turbine, etc., and their design requirements have been also introduced in this chapter. The underlying principles of the gas turbine designs for jet propulsion or for generating shaft power are discussed in Chapter 3. This covers the principles and methods of jet propulsion describing various types of jet engines, e.g., ramjet, turbojet, to turbo-rocket, and shaft power generation using simple or combined cycle power plants.

Chapter 4 discusses the material requirement in aircraft and land-based gas turbine, categorically classifying them according to the need in the different gas turbine components/sections, like inlet system, compressor, combustor, turbine, etc. The discussion includes many design aspects of these various components and their particular differences in applications in the aircraft and land-based gas turbines, as well as in the subsonic and supersonic jets. In Chapter 5, some material fundamentals related to the gas turbine application are discussed. This covers the importance of defects in structural materials that controls material behaviour (especially in crystalline lattices), fundamentals of strengthening of materials, alloying and thermodynamics aspects.

Chapters 6-9 covers the two most important groups of gas turbine materials, namely the Titanium alloys (including intermetallic based on Ti_3Al or TiAl) and Ni-base superalloys (including single crystal alloys). Two chapters are devoted on each of these two classes of alloys, where the first chapter deals with some fundamental aspects and the materials availability and the second devoting on how these alloys are manufactured, their developments and classifications. Ti-alloys are an important class of material in the low temperature end of the gas turbine, the inlet, compressor, etc., while the Ni-superalloys are irreplaceable in the combustor and the turbines. The high specific strength of Ti-alloys with their moderate temperature capabilities dominates in the inlet and the compressor components, but more recently with the introduction of TiAl-based intermetallic alloys, Ti-based materials are encroaching in the higher temperature turbine areas as well.

On the other hand, at the lower side of the temperature spectrum new material classes, like polymeric composites, carbon composite, metal matric composite, and ceramic matric composite materials, with favorable specific strength and stiffness are increasingly used as fan blades, etc.

Remarkably, Nickel superalloys are an unusual class of metallic materials with an exceptional combination of high temperature strength, toughness, and oxidation/corrosion resistance. Today superalloys are available that can tolerate service temperatures of 1100 °C, which incredibly is 80 % of their melting temperature. Moreover, it is exceptional that they are used in the gas turbine in a gaseous environment where the gas temperature is in excess of 1500 °C (much higher than the alloy's melting temperature). This has been made possible by special component cooling and thermal barrier coatings.

Gas turbines have benefited from the development of Ni-base superalloys for seven decades, but it is clear that the terminus ad quem point for the Ni-superalloys have now been reached. A new material class is needed for further gas turbine development to improve efficiency and make them more environmentally friendly (reduce CO_2 emission). In Chapter 9 in Outlook, ongoing research and development of some new materials are mentioned but its detailed coverage is beyond the scope of this monograph, which mainly deals with materials used in presently available gas turbines.

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Acknowledgements

Without the encouragement of Shri Amal Chakrabarti, ex-Director of DRDL, Hyderabad, a very close senior friend and a mentor, this monograph titled 'High Temperature Gas Turbine Materials' would never have been possible. Not only did he push me into accepting this challenge but also encouraged me in every step of this undertaking. I am an ex-DRDO employee but never worked with Shri Chakraborty, despite this he had faith in my capability, and that I find very reassuring. I would like to express my profound gratitude and thank him for his support.

I would also like to thank all my ex-colleagues at the Defence Metallurgical Research Laboratory (DMRL), Hyderabad, where I started my scientific career. At DMRL, for the first time I was introduced to gas turbines and its materials and these wonderful colleagues helped me to learn about the Ti-alloys. I particularly extend my sincere gratitude to all those at the Titanium Alloys Group (TAG), with whom I worked for the development of Ti-base alloys and intermetallic alloys. Some names stand out - Dr RL Saha, Dr D Banerji, Dr AK Gogia, Dr TK Nandy, Late Shri JG Kumar, Dr A Pradharkar, and Dr CR Chakravorty, who contributed to my understanding of this very important class of gas turbine material. Their contribution to this monograph is visible in the joint publications that I have cited throughout this monograph.

On moving to Europe in the 1990s there was also a shift in my research interest, which moved from the lower temperature compressor materials to the higher temperature turbine alloys. Here again, I am indebted to many colleagues with whom I worked, at first at the Hahn-Mietner Institute Berlin (HMI Berlin) and Technische Universität Berlin (TU Berlin), Germany and later at the Technische Universität Braunschweig (TU-BS), Germany and the Swiss Federal Institute of Technology Zurich (ETH Zurich), Switzerland. Working together with Late Prof H Wollenberger, Prof RP Wahi, Prof G Kostorz, Prof J Rösler, Dr G Schumacher, Dr N Wanderka, Dr H Gabrisch, Dr W Chen, Dr G Pigozzi, we solved many difficult challenges in Ni-superalloy development and that in turn enriched my knowledge of this crucial gas turbine alloy system. Again, their contributions to this monograph are vivid in the joint publications that I have cited throughout this monograph. I thank them all very much. Without their contribution this monograph was difficult to be realised.

Apart from the names I already mentioned there are two other colleagues, who deserve a very special mention. I met Dr Ralph Gilles (now at the Technische Universität München, MLZ, Germany) and Dr Pavel Strunz (now at the Nuclear Physics Institute of the CAS, Řež, Czech Republic) first at HMI where we jointly made small angle neutron scattering measurement on single crystal Ni-superalloy. In due course we all moved out of HMI, but we continued our collaboration for more than 25 years. This sustained effort resulted in more than 50 joint publications on gas turbine related materials over the period. Vielen Dank Ralph and Děkuji Pavel for your support. Many other colleagues from around Europe, joined our efforts from time to time and also profusely contributed to the research. I thank them as well, in particular, Dr P Beran (European Spallation Source, ESS, Lund, Sweden), Dr L Karge (MLZ, Germany), Dr L Szentmiklósi (Institute of Isotopes, Hungarian Academy of Sciences, Budapest, Hungary) and Dr H Eckerlebe (Helmholtz–Zentrum Geesthacht, Germany).

I must add, there are many other persons (including a vast number of students who worked quietly behind the scenes) with whom I also worked on the development of various gas turbine materials, list is rather long. I earnestly regret for not naming them individually, none the less, their contribution is immense, as can be seen from the many names in my joint publications. I am grateful to them all and thank them individually and profoundly for making this monograph possible.

The acknowledgement will not be complete without mentioning the support I got from the technical personnel in every institute I worked and without whom many of the experiments I performed would have not been possible. Again, the list is long but some names I cannot forget because I learned so much from them. Mr BS Prasad, Mr Baquer, Mr MT John, and Mr S Satyanarana, at DMRL, Hyderbad, Mrs Sabine Weber and Ms Dogmar Köpnick, at HMI, Berlin, Mrs Christa Grusweski and Mr Harold Scholz, at TU Braunschweig, Mr Erwin Fischer, at ETH Zürich, were the best support team any scientist can expect. Not only they knew their job, but they helped with their vast experience and knowledge to make each experiment a success. Many of them innovated the way samples were prepared or even modified and designed instruments we used to specially suit the experiments. I am greatly indebted for their support and thank them with my heart.

A very special thank is due to my wife Arundhati Mukherji, who not only supported my endeavor in all ways possible. She also took the pain to read through the text and correct mistakes. Not being a technical person in the field, I can imagine how boring it must have been for her to read through the nearly 400 pages full of technical jargons.

Last but not the least, sincere thanks are due to the entire team at Defence Scientific Information and Documentation Centre (DESIDOC), Delhi for their sincere and efficient support in bringing out this monograph. I would like in particular to thank heartily Ms Alka Bansal, Ms Kavita Narwal, Mr Rakesh Kumar and Mr NK Chawla.

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CHAPTER 1

Historical Perspective

1.1 EARLY METALS AND THEIR INFLUENCE ON HUMAN DEVELOPMENT

The development of human being is intensely linked to the discovery and use of different metals by man. So much so, that entire periods of early human existence are named after the metal that dominated the development in that period stretching thousands of years–examples: Copper Age (end of 5th millennium to beginning of 3rd millennium BC), Bronze Age (beginning of 3rd millennium to beginning of 1st millennium BC) and Iron Age (started around 1500 BCE*). The classification of the ages in this way is based on the consideration: "when did the smelting (the process of extracting metal from ore) of the specific metal actually started"? That is because when adequate quantity of the metal (/alloy) could be smelted, only then it was possible to shape it to useful objects to influence human life significantly. Even today, we live surrounded by metals, be it in our homes, when we are moving from place to place or in our work and leisure places.

Without materials, no object physically exists and amongst the materials, metals and their alloys and compounds dominate our living. This is no surprise, because if we look at the periodic table of elements (Fig. 1.1), of the 112 elements that are known to us (till recently**) 87 are metals. However, as already noted all metals that we use today were not

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* BCE (Before Common Era) and BC (Before Christ) mean the same thing and means before year 1 CE (Common Era).

** There is a recent extension of the periodic table which now contains 126 elements and include some elements which have been discovered very recently. Of the 126 known elements, 94 have been found naturally on Earth. The other 32 do not occur naturally, and instead have been synthesised in laboratories. Many of these new discoveries have extremely short half-life, which sometimes are in milliseconds.

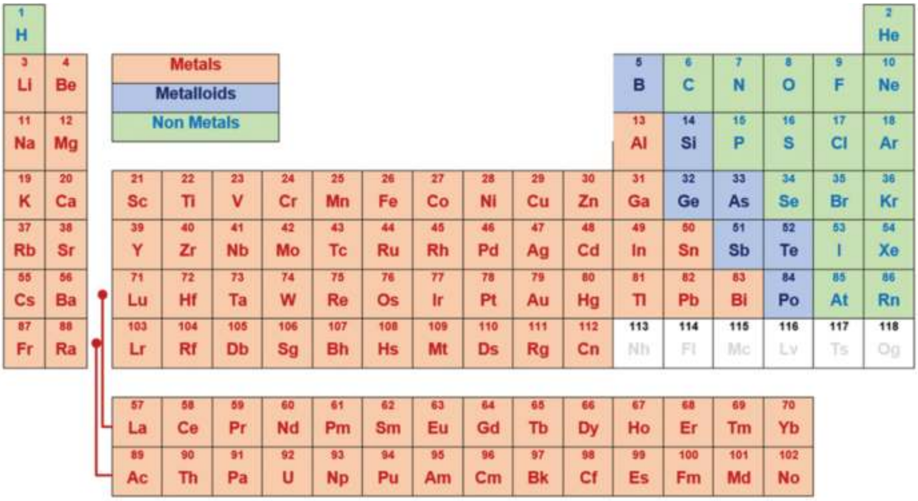

Figure 1.1. Periodic table showing metals metalloids and nonmetals.

discovered at the same period of time but over many thousand years. Only 7 metals were known to ancient man Before Common Era and the next 12 metals were discovered in the 18th century. Till the start of the Industrial Revolution, only a little more than two-thirds (60) of the 87 metals were discovered (see timeline in Appendix). So, a question comes to mind, why did it take so long? Amongst many factors, the reactivity of the metal and its abundance in the earth's crust played a crucial role in their discovery and extraction.

Gold is the first metal to be found by ancient man before 6000 BCE. It is no coincidence, because gold (chemical symbol Au) is a noble metal and one of the few metals that exists in its pure form in nature. Even the noble metal silver (Ag), which was discovered about 2000 years later, oxidises readily in atmosphere. Moreover, gold because of its metallic luster and its shiny golden colour reflect light and make it visible even when found in a mix of stone and dust on the earth's surface. Surely, these shiny specks of matter attracted ancient man, although only a very tiny fraction of gold exists on the earth's crust. The extent different elements in the periodic table are available on the earth's crust (abundance expressed in parts per billion by weight) is shown in Fig. 1.2. The data is taken from the source cited in reference.[1]

Despite the early discovery of gold and even though the next metal copper (Cu) was not discovered in more than thousands of years, there is

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About the Monograph

Gas turbines used in aeroengines, as well as their land-based applications, are very complex devices. Their different sections (compressor, combustor, turbine, etc.) are subjected to varying temperatures and pressures by the high-velocity and extremely corrosive/erosive/oxidising gas flowing through them. The temperature (in excess of 1500 °C) in some components, like the rotating turbine blades, even exceeds the melting temperature of the metallic alloys the blades are made from. To meet these extreme challenges, not only innovative designs have been used in gas turbines (e.g., cooling, and thermal barrier coatings) but also a wide range of high-performance materials are needed to construct the gas turbines. These encompass different metallic alloys, ceramics, ceramic- or metal-matrix composites, and intermetallic alloys. Development of high-performance gas turbine engines has been made possible only through the remarkable development of new materials and innovative processing over the past 70 to 80 years. This development continues and is particularly driven by military jet engines, making the subject of gas turbine material very important for a wide range of industries.

The monograph discusses gas turbine materials (with emphasis on Ti-alloys and Ni-superalloys). It is essentially a book on material science. However, due to the complexity of gas turbines and their wider appeal, it is of equal interest for both the material scientists and the mechanical/aeronautical engineers involved in gas turbine development and maintenance. The monograph begins with a historical perspective of turbine development and covers some basic principles of jet propulsion and material science. However, the main emphasis remains on the high temperature gas turbine materials – their manufacturing from alloy to components, as well as their development and applications.

About the Author

Dr Debashis Mukherji started his research career as a Junior Scientific Officer at the Defence Metallurgical Research Laboratory (DMRL), Hyderabad, after graduating in Metallurgical Engineering from the Indian Institute of Technology (IIT), Kharagpur, India in 1976. He was awarded PhD degree by IIT, Kharagpur in 1987 for his research on the Development of Titanium alloys using electron microscopy. Shortly after completing his PhD, he moved to the Hahn Meitner Institut and the Technische Universität Berlin, Germany as a postdoc fellow and later became a Research Scientist there and pursued research on the Development of Nickel base superalloys. Both Ti-alloys and Ni-superalloys are critical gas turbine materials.

In 1998 he joined the faculty at the Technische Universität Braunschweig (TU-BS), Germany, and in between for a short period (2003-2005) has also worked at Swiss Federal Institute of Technology Zurich (ETH), Zurich, Switzerland. Throughout his career he worked for the development of gas turbine materials and in the later stage developed a new class of Co-Re-based superalloys for higher temperature application than Ni-superalloys.

He is a specialist in electron microscopy alongwith other scattering techniques, including neuron and synchrotron scattering methods for in-situ studies at high temperatures. He coordinated high temperature material research in collaboration at large research facilities around Europe that included Elektronenspeicherring-Gesellschaft für Synchrotronstrahlung (BESSY) in Berlin, Forschungsreaktor München II (FRM II) in Munich, Deutsches Elektronen-Synchrotron (DESY) in Hamburg, Paul Scherrer Institut (PSI) in Switzerland, Nuclear Physics Institute (NPI) in Czech Republic, Budapest Neutron Centre (BNC) in Hungary and European Spallation Source (ESS) in Lund, Sweden. This collaboration effort between 1993-2019 produced a large number of publications related to high temperature materials and nano-structured materials. He also participated in several pan German and joint European projects for development of gas turbine material beyond Ni-base superalloys. While working at DMRL he was a member (expert on Ti alloys) of the Kaveri Engine Development Board for Light Combat Aircraft coordinated by Gas Turbine Research Establishment (GTRE), Bengaluru.

He has more than 220 publications in international journals including 3 books/book chapters and 4 German and European patents. He has made more than 100 presentations at national and international conferences and has won several awards.

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