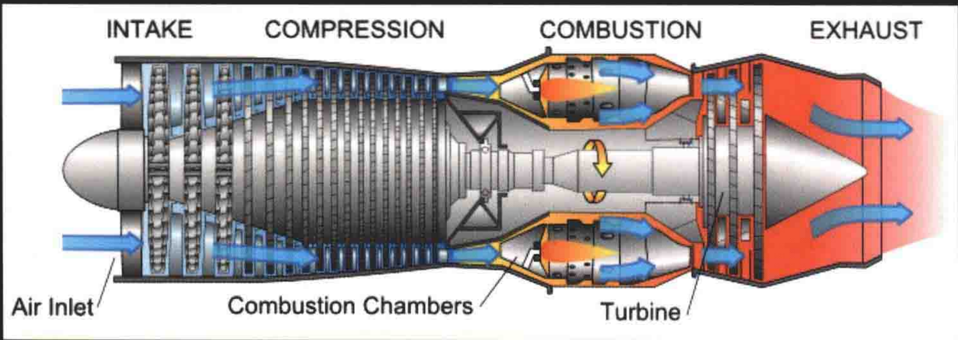
A. S. Khanna

# High Temperature Corrosion




World Scientific

# High Temperature Corrosion


**A. S. Khanna**
Indian Institute of Technology, Bombay, India

World Scientific
NEW JERSEY • LONDON • SINGAPORE • BEIJING • SHANGHAI • HONG KONG • TAIPEI • CHENNAI • TOKYO

*Published by*

World Scientific Publishing Co. Pte. Ltd.
5 Toh Tuck Link, Singapore 596224
*USA office:* 27 Warren Street, Suite 401-402, Hackensack, NJ 07601
*UK office:* 57 Shelton Street, Covent Garden, London WC2H 9HE

**Library of Congress Cataloging-in-Publication Data**
Names: Khanna, Anand S.
Title: High temperature corrosion / [edited by Anand S. Khanna].
Description: New Jersey : World Scientific, 2016. | Includes bibliographical references and index.
Identifiers: LCCN 2015031963 | ISBN 9789814675222
Subjects: LCSH: Corrosion and anti-corrosives. | Materials at high temperatures.
Classification: LCC TA462 .H5236 2016 | DDC 620.1/1223--dc23
LC record available at http://lccn.loc.gov/2015031963

**British Library Cataloguing-in-Publication Data**
A catalogue record for this book is available from the British Library.



Desk Editor: Kalpana Bharanikumar

Typeset by Stallion Press
Email: enquiries@stallionpress.com

Printed in Singapore by B & Jo Enterprise Pte Ltd

# High Temperature Corrosion

# Foreword

High Temperature Corrosion is a serious problem for many industries. Fossil-fueled power plants, refineries, petrochemical plants, chemical processing plants, operating at temperatures ranging from 400°C to 1100°C, have severe corrosion problems. Fireside corrosion in coal-based power plants, steamside corrosion, sulfidation and carburization problems in refineries and petrochemical plants, and direct chemical attack in the chemical process industries are a few problems which still need solution. Solution to high temperature corrosion problem can be tackled in two ways, first by properly selecting the materials and second by controlling the environment. I think the better solution is proper selection of materials. Development in metallurgy over the years has given several new and advanced materials, starting with specialized steels, stainless steels, superalloys, ceramics and composites. However, selection for specific application needs knowledge of metallurgy, materials science and corrosion. Degradation of materials at high temperatures occur due to both loss in mechanical properties as well as degradation due to corrosion, which can be oxidation, sulfidation or hot corrosion. Hence selection of materials must take into account the synergistic effect of mechanical properties and corrosion. This has been very nicely covered in Chapter 2 from a beginner's prospective and can guide in proper selection of materials at high temperatures. This information coupled with basic knowledge of high temperature corrosion, given in Chapter 1, in terms of stability and kinetics for various advanced materials, can ease the selection process. Chapter 3 provides the basis of the development of advanced materials. Chapters 4–6 are the backbone of this book that present the industrial scenario of degradation of materials in three important sectors — chemical and petrochemicals industry, power plants and aerospace industry. It is well known that even a highly well-developed material still needs protection at the surface. Properties such as hardness, corrosion protection cannot be achieved by bulk alloy development. Hence, Chapter 7 is devoted to various kinds of coatings used to protect materials at high temperatures. To understand the mechanism of oxidation process, it was planned to introduce a chapter on analytical tools to analyze corrosion products. But instead, a specific versatile technique has been included in Chapter 8 which can give very useful information about oxides scales and corrosion layers formed during high temperature exposure. No book can be complete without talking about nanotechnology. The next chapter, that is Chapter 9 focuses on a very important aspect of high temperature corrosion that is active element effect. The chapter very nicely summarizes the present understanding of active element addition and on the stability of oxide layers. A specific example of the use of nanoparticles in the development of high temperature resistant surface coatings has been covered. The last chapter, that is Chapter 10 includes information on reactive element effects.

In short, the book provides fundamental knowledge about high temperature corrosion, development of advanced materials, interaction of corrosion and mechanical properties, corrosion related problems in three important industries and topics such as coatings and nanotechnology. The book can be taken as an advanced information for this topic and can be used as a reference book as well.

It is my pleasant duty to thank all my authors who have contributed the various chapters. Prof. Ukai of Hokkaido University, Japan, Dr. Kangas from Sandvik India, Prof. Raman Singh and his colleague Mahesh from Monash University, Dr. Joe Quaddakers and his Colleague Dimitri from Forschungs Zentrum Juelich, Germany, Dr. Subrato Mukharjee and my Student Nirav Jamanapara from

IPR, Gandhinagar, India and finally to my friend Dr. Vinod Agarwala, retired scientist, US Navy, for helping me on the chapter on corrosion problems in aerospace industry.

I sincerely hope this book will be of immense benefit to new readers and will act as a source book for personnel working in power plants, refineries and aerospace industry.

Prof. A. S. Khanna,
Humboldt Fellow,
Fellow of Royal Norwegian Science and Technology,
Fellow Japan Key Centre,
Fellow ASM International and NACE International,
Chairman SSPC India,
Department of Metallurgical Engineering & Materials Science,
IIT Bombay, India.

# Overview

1. **Fundamentals of High Temperature Oxidation/ Corrosion**
   Prof. A. S. Khanna, IIT, Mumbai, India
   Criteria of metal oxidation, sulfidation and hot corrosion at high temperatures, kinetics of oxidation, sulphidation and hot corrosion, modeling to assess the life and durability of materials at high temperatures in different environments.
2. **Degradation of Mechanical Properties of Materials at High Temperatures in Corrosive Environments**
   A. S. Khanna, IIT Bombay, India
   Degradation of mechanical properties such as tensile strength, fatigue and creep at high temperature with and without the presence of corrosive gases such as air, oxygen etc. Models to understand the synergistic effect of temperature and environment on mechanical properties.
3. **Materials Development Aiming at High Temperature Strengthening — Steels, Superalloys to ODS Alloys**
   S. Ukai, Hokkaido University, Japan
   Fundamental metallurgical principles to develop high temperature materials, role of microstructure, alloying, strengthening mechanism and method of fabrication on the high temperature properties of materials.

**4. High Temperature Corrosion Problems in Refineries, Chemical Process Industries and Petrochemical Plants**

Pasi Kangas, Sandvik Materials Technology, Pune, India

Material failure leading to accidents and plant shut down in various chemical process industries, refineries and petrochemical plants, use of better materials, proper control of environments, especially sulfur bearing gases and development of models to select better materials.

**5. High Temperature Corrosion Problems in Coal-Based Thermal Power Plants**

A. S. Khanna, IIT, Mumbai, India

Complete description of various kinds of power plants, fossil fueled, fluidized bed, nuclear reactors, fireside problems in fossil fueled power plants, fuel/clad problems in nuclear reactors, steam side corrosion problems, new materials for super critical power plants.

**6. High Temperature Corrosion Problems in Aircrafts**

A. S. Khanna and Vinod S. Agrawal

Aerospace industry uses one of the most corrosion resistant materials. Description of various degradation mechanisms in aircraft gas turbines, combustion chamber and use of advanced materials.

**7. Coatings for High Temperature Applications**

N. I. Jamnapara and Subrato Mukherjee, Institute of Plasma Research, Gujarat, India

Starting with surface modification methods, classification of various high temperature coatings, based on functional application, techniques used, detailed methodology with pros and cons of the coating, examples of a few specific examples where role of coating has been emphasized.

**8. Advanced Analytical Tools to Understand High Temperature Materials Degradation — Ion Beam Characterization of Aerospace Materials**

Barbara Shollock, University of Warwick, UK and David S. McPhall, Imperial College of London, UK

Starting from basics of optical and electron optical techniques, a coverage of advanced techniques such as AES/ESCA, SIMS, focused Ion beams, AFM etc.

9. **Role of Nanotechnology in Combating High Temperature Corrosion**
Raman Singh, Monash University, Australia, B.V. Mahesh and Prabhakar Singh, Centre of Clean Engineering, University of Connecticut, USA

    Fundamental principles of nanotechnology in materials development, role of nanopowders in making high performance surface coatings, their advantages and limitations.

10. **Reactive Element Additions in High Temperature Alloys and Coatings**
D. Naumenko and W.J. Quadakkers, Institute for Energy and Climate Research (IEK-2), Forschungszentrum Jülich GmbH 52425, Jülich, Germany

    Mechanisms and effects of reactive elements.

## Addresses of Corresponding Authors

1. A. S. Khanna,
   Department of Metallurgical Engineering & Materials Science,
   Indian Institute of Technology, Mumbai – 400076, India.
   anandkh52@ggamil.com.
2. S. Ukai,
   Laboratory of Advanced High Temperature Materials,
   Research Group of Energy Materials, Division of Materials
   Science and Engineering,
   Hokkaido University, Japan.
   s-ukai@eng.hokudai.ac.jp.
3. Pasi Kangas,
   Sandvik Materials Technology
   Mumbai Pune Road, Dapodi, Pune 411012, India.
   passi.kangas@sandip.com
4. S. Mukherjee,
   Institute of Plasma Research, Gandhinagar, Gujarat, India.
   mukherji@ipr.res.in
5. David S. McPhall,
   Department of materials
   Imperial College London
   Room No. 1.02, Royal School of Mines Building
   South Kensington Campus
   London – SW7 2AZ, UK.
   d.mcphall@imperial.ac.uk

6. Raman Singh,
Department of Mechanical & Aerospace Engineering
Department of Chemical Engineering
Bldg 31, Monash University — Clayton Campus (Melbourne)
Vic. 3800, Australia.
raman.singh@monash.edu
7. D. Naumenko
Institute for Energy and Climate Research (IEK-2)
Forschungszentrum Jülich GmbH 52425
Jülich, Germany.
D.naumenko@fz-juelich.de

# Biography

Dr. A. S. Khanna is Professor at The Indian Institute of Technology, Bombay, India with responsibility for teaching, research and consultancy in the fields of corrosion, coatings, surface engineering and corrosion management.

Prior to joining IIT Bombay, Prof. Khanna worked in the department of Atomic Energy with a focus on high temperature corrosion problems on power plant materials. He visited several international labs/universities/institutions, including Forschungszentrum, Juelich, Oslo University, University de Provence, Marseille France and IHI Heavy Industry, Japan.

His professional interests focus on coatings, industrial corrosion prevention, surface engineering, high temperature materials, high temperature coatings, laser surface modifications. He has already guided 22 PhD's, out of which more than 14 are on high temperature corrosion, high temperature coatings and laser alloying. His current projects include development of smart coatings and nanotechnology for enhancing organic coating performance. He is Consultant/ Advisor to many industries, including oil and gas, refineries, power plants and petrochemical plants. He has written two books, one is on High Temperature Corrosion, published in 2002 by ASM

International, Ohio, USA. His second book is on High Performance Coatings, published by Woodhead publication UK in 2008. He has also edited four conference proceedings. In addition, he serves as Chairman for SSPC India, and is Fellow of NACE International and Fellow of ASM International.