

Foreword

In industries, there are many processes operated at elevated temperature under severely corrosive atmospheres. High temperature corrosion (HTC) may degrade the performance and the life of metals and alloys which are involved in the processes. The protection of the materials from HTC is a key issue.

High temperature oxidation (HTO) is the most frequent phenomena in HTC. Metallic alloys are exposed to the gaseous oxidants (O_2 , H_2O , CO_2 , SO_2 , NO_2 etc.) at elevated temperatures. Metallic constituents are oxidised and form the oxide scale (oxide layer) on the surface. In the case of the oxide scale being dense enough to separate physically the metal and the oxidant, the oxidation process is rate determined by diffusion of ions through the layer and the oxidation rate is slowed down dramatically. Prior to the scale formation, less noble constituents are oxidised by dissolved oxygen in the alloy and oxide precipitates form internally (internal oxidation). The increase in the number of precipitates and their coarsening result in the combination of precipitates and the formation of continuous oxide scale (external oxidation). During mass transport process of oxidation, complex microstructure developments such as oxide grain growth and void (pore) formation strongly affect the stress generation and exfoliation of oxide scales. Furthermore, the grain boundaries in the oxide scale may serve short circuits of ionic diffusion.

High temperature oxidation seems to be so complicated for engineers to understand and protect materials from HTO. The clarification of HTO requires more researches and basic knowledge of thermodynamics and kinetics.

Professor Alain Galerie is one of the most recognised figures in the French and global HTC community. He started his work on HTC from 1970 and he has continued in five decades. His style of research is to focus on elemental phenomena which govern the chemical and mechanical features in HTC by using microscopic analytical techniques, which helps largely for understanding the mechanism of HTO/HTC. He has been invited to give lectures from major scientific congresses such as Gordon Research Conference on HTC, International Symposium on HT Corrosion and Protection of Materials (the Embiez Congress) and so on. He is also author or co-author of several books. There are excellent professors and engineers in HTC community not only in France but also in the world, whom he educated as a teacher and a supervisor.

This book is published by the contribution of Professor Alain Galerie's former students, the colleagues in his research group and leading researchers in the field. This book offers briefly the basic knowledge and the recent understanding on HTC of stainless steels so that it is beneficial to graduate students and young researchers in HTC community.

Toshio Maruyama
Professor Emeritus,
Tokyo Institute of Technology, Japan

Preface

This book provides the basic concepts and the recent research on the high temperature corrosion of stainless steels, starting from the introduction to stainless steels in the early part of Chapter 1. Thermodynamics and kinetics of high temperature corrosion phenomena, as well as mechanical behaviour of thermal oxide formed on the metal are treated in Chapters 1 and 2. Chapter 3 explains tools to characterise the thermal oxide scale. Applications on stainless steel oxidation are given in these three chapters. The effects of alloying elements and the atmosphere emphasising on water vapour on stainless steel oxidation are further addressed in Chapters 4 and 5. The last chapter devotes to the specific application of stainless steel as an interconnect in solid oxide fuel cells (SOFCs).

Because this festschrift is published in honour of Professor Alain Galerie, selection of the presented topics and recent research therefore reflect his style and the works conducted by his group and his alliance. For example, the treatment of the high temperature corrosion phenomena by using defect reactions is favoured here following his style. The experimental set-ups developed in his group are highlighted particularly the photoelectrochemical technique, the set-up to measure chromium species volatilisation and the mechanical adhesion energy measurement. His interest in the oxidation in water vapour and the development of stainless steel SOFC interconnect are also emphasised.

This book stems from the “Alain Galerie Symposium on High Temperature Corrosion” which was held at King Mongkut’s University of Technology North Bangkok (KMUTNB), Bangkok, Thailand, on 9 July 2018. Fortunately, the book was finished in the period of the celebration of the 30-year anniversary of the KMUTNB Thai-French Innovation Institute established since 1990. The editors appreciate Professor Toshio Maruyama for his foreword. They sincerely thank the co-authors and anonymous reviewers for the contribution to this book. The acknowledgement is given to the assistants to the editors: Ms. Thammaporn Thublaor and Mr. Panya Wiman.

The editors hope that this book will be useful for the high temperature corrosion community. Further, they do hope that this festschrift will be an academic monument to show the contribution of Professor Alain Galerie to this field, and to express our love and respect to him.

The editors

Somrerak Chandra-ambhorn
Professor,
KMUTNB, Thailand

Yves Wouters
Professor,
Université Grenoble Alpes, France

Wanlop Harnnarongchai
Assistant Professor,
KMUTNB, Thailand

Alain Galerie: A Biography

Yves Wouters^{1,a*} and Somrerk Chandra-ambhorn^{2,b}

¹Université Grenoble Alpes, SIMaP, 1130 rue de la Piscine, BP 75, 38402 St Martin d'Hères, France

²High Temperature Corrosion Research Centre, Department of Materials and Production Technology Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, 1518, Pracharat 1 Road, Bangsue, Bangkok, 10800, Thailand

^ayves.wouters@univ-grenoble-alpes.fr, ^bsomrerk.c@eng.kmutnb.ac.th



Professor Alain Galerie is, to this day, one of the most recognised figures in the French and global high temperature corrosion community. His entire career demonstrates his great attachment to his job as a teacher-researcher.

Since 1970, he has been studying the theoretical study of the kinetics of reactions between composite gases and metals, including sulphurisation, developed in his thesis in 1977. Thereafter, and until now, he has continued to tackle new scientific projects often characterised by innovative research and with multiple outcomes. During several postdoctoral research stays at the Harwell Nuclear Center (UK), he got passion with ion implantation and its effects on oxidation, then on the development of making solidified surface alloys under a laser beam. The research on ion implantation into metals led him win the “Prix Lucien Chatain” from the French South-East Scientific Foundation. In the 90s, when few scientists saw the interest, he began, with Marcel Caillet, DR CNRS, a vast program of study of the effects of water vapour on the oxidation at high temperature of pure metals. It is only a decade later that the community will become aware of the inevitable interest of this subject, water vapor being revealed, in many industrial environments, as an extremely aggressive agent. Thanks to this expertise, he was invited to give two plenary lectures to the Gordon Research Conferences in 2001 and 2009. He was also interested in the contribution of photoelectrochemistry, technique which has proven to be very successful in bringing innovative information thanks to the semiconducting signature of oxide scales. Later, he developed a new major axis around the adhesion of thermal oxides to refractory alloys by implementing tools for determining the interfacial rupture energy of the protective layers (blister test and SEM *in-situ* tensile testing). He also studied the monitoring of damage during high temperature oxidation by acoustic emission. In addition, he was involved in a perpetual action of newness, for example with the use of Raman imaging and FIB/SEM in several studies. All of this work was done with 30 PhD students. As the industrial development is growing up in Asia, he and his group have supervised 5 PhD students from Thailand who are now actively working in research in their region, as well as a number of interns from Thailand.

As a result of the research works, he produced more than 180 papers in scientific journals and proceedings (163 articles referenced "Web of Science", h-index = 23) and more than 50 invited lectures. He is regularly invited as a member of thesis and HDR (habilitation thesis to supervise

research) juries. He involved, nationally as well as internationally, in the organisation of thematic schools and major scientific congresses - the most famous being probably the International Symposium on High-Temperature Corrosion and Protection of Materials (better known as name of the Embiez Congress). Although now retired, Professor Alain Galerie is still very active. He is regularly invited in the major congresses of the high-temperature oxidation community in which he gives very popular scientific historical lectures.

Professor Alain Galerie is also author or co-author of several books, the most notable of which is "Les mécanismes de la corrosion sèche" with his colleagues Pierre Sarrazin and Jacques Fouletier, published in French in 2000. This book won the "Roberval Prize" in 2001 and was translated into English version (Mechanisms of High Temperature Corrosion: A Kinetic Approach) in 2008. He also wrote the eight papers published in the "Techniques of the Engineer" with Laurent Antoni. He won the "Ugine-René Castro Prize" from the French Society for Metallurgy and Materials in 2005, and the "Grande Médaille" from the French Centre of Anticorrosion in 2010.

He spent most of his career at ENSEEG (National School of Electrochemistry and Electrometallurgy of the Polytechnic National Institute of Grenoble), where he was for many years the Director of Studies. He has also held, at the national level, the position of President of the "P" and "PSI" Concours Communs Polytechniques. His teaching has always been, for him, a priority and he constantly privileged the close relationship with students, advocating for the strengthening of practical work and laboratory projects. In addition to mineral chemistry, he has taught in particular heterogeneous kinetics, high temperature corrosion and surface treatments. The school PHELMA / Grenoble INP, today formed by the meeting of three Grenoble schools, owes a lot to him in his new organisation. Having trained many engineers and PhD students whom he likes to meet often in the research and development centres of the big French industrial groups, Professor Alain Galerie is known for his remarkable pedagogy and his great attachment to the training of the students, qualities which have undoubtedly helped to mark several generations of young researchers.

Research Group

Shigenari Hayashi
Hokkaido University, Japan

Walairat Chandra-ambhorn and Patthranit Wongpromrat
King Mongkut's Institute of Technology Ladkrabang, Thailand

Somrerak Chandra-ambhorn, Wanlop Harnnarongchai, Thanasak Nilsonthi, Piyorose Promdirek,
Anusara Srisrual and Thammaphorn Thublaor
King Mongkut's University of Technology North Bangkok, Thailand

Sébastien Chevalier, Lionel Combemale and Ioana Popa
Université de Bourgogne Franche-Comté, France

Muriel Braccini, Laurence Latu-Romain, Valérie Parry, Céline Pascal and Yves Wouters
Université Grenoble Alpes, France

Group Pictures at Alain Galerie Symposium on High Temperature Corrosion, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand, 9 July 2018.



From left to right: Somrerck Chandra-ambhorn, Thanapat Kaewmaneeekul, Toshio Maruyama, Shigenari Hayashi, Yves Wouters, Suchart Siengchin, Alain Galerie, Vincent Drapeau, Laurance Latu-Romain, Sébastien Chevalier, Valérie Parry, Thammapun Thublaor and Wattana Kaewmanee



From left to right: Supat Ieamsupapong, Somrerck Chandra-ambhorn, Thanasak Nilsonthi, Walairat Chandra-ambhorn, Piyorose Promdirek, Alain Galerie, Yves Wouters, Patthranit Wongpromrat, Valérie Parry, Laurence Latu-Romain and Anusara Srisrual