




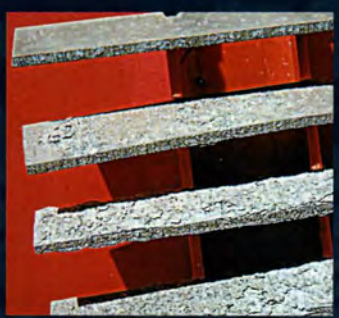

Corrosion of Aluminium

SECOND EDITION

Christian Vargel

ELSEVIER

Corrosion of Aluminium

Second Edition

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Consulting Engineer on Corrosion of Aluminium
www.corrosion-aluminium.com

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Contents

PART E

PART F

PART I

PART K

Foreword

If there is a metal of the future, it is aluminium.

Aluminium's success has been consistent for over 100 years. Most recently, at the start of the 21st century, annual consumption of aluminium reached 29 million metric tons; by 2017, that figure had risen to 80 million metric tons. And some are predicting consumption could reach about 120 million metric tons in 2030.

This is hardly a surprise. Aluminium's intrinsic properties make it a unique and extremely virtuous material that responds to numerous challenges in our society linked to climate change and responsible management and protection of the Earth's resources. Aluminium's ability to be endlessly recyclable without losing its initial properties is an excellent example of this.

Furthermore, thanks to its lightweight capability, aluminium allows transportation vehicles on land, in the air and at sea to significantly decrease fuel consumption and thus drastically reduce emissions of greenhouse gases. It also combines ductility and a high level of resistance to both impacts and corrosion.

Beyond its specific properties, the inexorable fascination with aluminium is first and foremost the result of decades of research and innovation. Generations of researchers have worked on the development of increasingly advanced alloys and ever-more innovative manufacturing processes.

This is particularly the case with the technique of friction stir welding, which makes it possible to assemble different materials without the need for rivets or additive manufacturing processes, also known as 3D printing.

At Constellium—a successor of the Pechiney, Alcan and Alusuisse groups and a global leader in innovative, high value-added aluminium solutions—we make sure engineers and technicians in our R&D centre have access to the most sophisticated resources and methods available. Thanks to many close collaborative projects with our customers and numerous laboratories and universities worldwide, Constellium has designed unique and revolutionary solutions such as Airware for the aerospace sector, Securalex and HSA6 for the automotive industry and Aeral for aerosol packaging.

Although they are used in different applications and come from a wide range of families of alloys, these new products highlight our industry's quest for excellence and our ability to imagine the world of the future through continuous optimization of the properties of aluminium.

One of the fundamental areas of research is corrosion, the subject of this book. Although it is naturally resistant, aluminium needs to offer ever-higher performance. This new edition of Christian Vargel's book, *Corrosion of Aluminium*, reflects the knowledge he has accumulated over his 40 years at Pechiney as an engineer in our research centre. As a speaker and author of several books on the metal, Christian Vargel is a recognized expert in the field of aluminium corrosion, or as he would put it, a corrosion practitioner.

Thanks to its scientific approach to the topic, this book is both an exploration of the phenomenon of aluminium corrosion and a practical guide to the use of aluminium alloys based on their corrosion properties. Aimed at both academics and professionals, it is unrivalled in its field and I would like to offer the author my warmest thanks for entrusting its foreword to me.

Jean-Marc Germain
Chief Executive Officer, Constellium

Foreword to the original edition

With an annual consumption of 25 million metric tons, aluminium is the second most commonly used metal in the world after steel. Its lightness is very often the most important advantage for the commercial development of aluminium, which explains why it is extensively used for ground transport, aerospace and shipbuilding. This is also the reason why the automotive industry is currently very interested in aluminium: lightness is becoming a priority.

The second advantage of aluminium is its corrosion resistance. This explains its important position in construction, civil engineering, transport, heat exchangers and so on.

In 1890, naval architects had considered aluminium for reducing weight in vessels. But in order for aluminium to be useable for shipbuilding, metallurgists and corrosion specialists in the 1930s first had to develop aluminium magnesium alloys. These alloys have an excellent corrosion resistance in the marine environment, and they are weldable. Since 1960, all high-speed ferries have been built in these alloys.

A similar trend was observed with heat exchangers: aluminium was recognized as an obvious solution, especially for automotive heat exchangers since 1970. In fact, several alloys have very good thermal conductivity and excellent resistance to engine coolants, making it possible to manufacture heat exchangers that are cheaper and of course lighter than traditional heat exchangers in copper alloys.

Projects for developing renewable energy sources (solar, etc.) have often been based on the use of aluminium heat exchangers for several reasons: a much lower cost than titanium, good thermal conductivity and excellent corrosion resistance.

Christian Vargel, throughout his long career within Pechiney, has been a practitioner of aluminium corrosion and a recognized expert in this field. His first book, *Le Comportement de l'Aluminium et de Ses Alliages* (*The Behavior of Aluminium and Its Alloys*), was published by Dunod in 1979.

Since then, his experience has grown steadily. He has followed marine applications and automotive heat exchangers and has participated in many damage assessments involving corrosion in service. He has also given many talks on the corrosion resistance of aluminium, and has contributed to many of Pechiney Rhenalu's technical documents and brochures, such as 'Aluminium and the Sea' and 'Aluminium in Industrial Vehicles'. We therefore encouraged him in his project to write a second book: his recognized experience in the field of aluminium corrosion deserved to be more widely known and disseminated. This book will certainly contribute to meeting this goal.

Corrosion is a difficult topic. I am deeply convinced that the practitioner's approach, based on expertise and experience, is best for assessing the corrosion resistance of aluminium, an assessment that is obviously one of the main conditions for the development of many uses of aluminium in transport and construction power transmission.

Christian Vargel's book presents the reader with a global approach to corrosion, comprising the selection of alloys, design principles and service conditions. I am convinced that it will contribute to the development of aluminium in those fields where resistance to corrosion is an essential property.

Bernard Legrand
Former Deputy Chief Executive Officer
Pechiney, September 1998

Preface

My long career in the Pechiney Group from 1957 to 1997 and subsequently as an independent consultant principally focused on aluminium corrosion has enabled me to acquire extensive experience in this field.

My experience is based on the treatment of the many cases of in-service corrosion that I have had to deal with over the past 50 years, and on the electrochemical and metallurgical fundamentals of aluminium corrosion.

This dual approach has made me a corrosion practitioner, in the sense that I had to find an explanation for cases of corrosion in service or that I had to plan how to avoid it through the choice of alloys, operating conditions and so on.

Indeed, corrosion remains a complex subject because it depends on many parameters, which makes it necessary to have a practical approach to be useful and explainable on the basis of fundamental data.

This engineering activity has allowed me to acquire wide experience in aluminium applications, particularly where the question of corrosion resistance of buildings, heat exchangers, renewable energy systems (solar, OTEC, etc.), transport, shipbuilding and so on is concerned.

I have frequently shared my experience of aluminium corrosion at numerous conferences and in several brochures published by Pechiney: "Aluminium and the Sea," "Aluminium in the Automotive Industry," "Aluminium in Industrial Vehicles," and "Aluminium Semi-finished Products."

Following a request of the publisher, Elsevier, I resumed the reediting of the first version of *Corrosion of Aluminium* published in 2004, which was the translation of *Corrosion de l'Aluminium* published in French by Dunod in 1999.

In this new edition, I have reviewed and incorporated the knowledge acquired recently by many laboratories that have published on the subject of aluminium corrosion and its metallurgical aspects. In 20 years, new investigative methods have also made it possible to explain many of the phenomena involved in structural corrosion.

As a result, this new edition of *Corrosion of Aluminium*, while maintaining its practical orientation to meet the needs of aluminium users, gives a large place to the results of the high-quality scientific publications of the many researchers dedicated to the study of aluminium corrosion.[1]

Like the previous version, this new edition aims at a wide readership ranging from aluminium users to academia. Both will find useful information on aluminium corrosion based on the state of knowledge acquired up to the time of writing this new edition.

I would like to thank all those who have given me their precious support in the writing of this book:

- Dr Lionel Peguet, corrosion and surface R&D engineer, CTEC Constellium Technology Centre, Voreppe, France
- Jean-Sylvestre Safrany, research engineer, Surface Treatments, CTEC Constellium Technology Centre, Voreppe, France
- Françoise Saillard, information specialist, CTEC Constellium Technology Centre, Voreppe, France
- Damien Féron, CEA Saclay, France, president of the European Corrosion Federation
- Bruno Savelli, CEA Saclay, France, Direction de la Recherche Fondamentale, Service de Valorisation de l'Information

[1] Over 2000 publications on aluminium corrosion published from the beginning of the 20th century up to the present day have been cited in this book.

➢ Philippe Marcus, director of research at the Centre National de Recherches Scientifique (CNRS), Chimie ParisTech
➢ Michel Jannier, expert in aluminium surface treatment processes
➢ Michel Pinçon, expert in aluminium surface treatment processes
➢ Michel Garat, aluminium foundry consultant, former Pechiney R&D manager
➢ Hassina Founas, executive assistant of the French Anti-Corrosion Centre (CEFRACOR), Paris

I would like to thank Hugh Dunlop for agreeing to translate my text into English. I chose Hugh because of his experience and knowledge of aluminium surface phenomena and surface treatments, having been an engineer and group leader in the Constellium CTEC Voreppe Research Centre (formerly Pechiney & Alcan) for 27 years and himself the author of many publications.

I would also like to express my thanks to Geoff Scamans, chief scientific officer at Innoval Technology (Banbury, UK) for his expert review of several chapters, particularly those relating to the different types of aluminium corrosion. I am very grateful for his knowledgeable input.

I would like to express my gratitude once again to André Guilhaudis (1918–2008), who was Pechiney's corrosion expert from 1945 to 1980. He welcomed me to the Pechiney Research Centre in Chambéry in 1957 and shared with me his passion for aluminium and his experience in corrosion.

C. VARGEL
Ingénieur ENSEEG
15 November 2019

Introductory remarks

It is customary, and for convenience, to refer to aluminium, but what is meant in most cases are aluminium alloys. It should be recalled that unalloyed aluminium accounts for just over 10% of the world's annual consumption of all aluminium products.

However, for the sake of simplicity, I use 'aluminium' instead of the traditional expressions 'aluminium and its alloys' or 'aluminium and aluminium alloys'. It should not be concluded that the corrosion resistance of all aluminium alloys is the same in any environment! There are certainly some similarities, but there are also important differences between 2XXX and 7XXX series alloys and those of the other families. That is why I have made this distinction whenever appropriate.

When one or more alloys have been used for corrosion tests in a given environment, it seemed desirable to me to mention them because they were part of the test protocol chosen by the scientists and contributed to its validation. Similarly, it seems essential to indicate the alloys commonly used in an application. These are references that help to establish the use and strengthen the choice of prescribers and users.

The designation of wrought and cast alloys employed is that of the Aluminum Association[1] [1]. To facilitate the reading of Parts E and F dealing with the corrosion resistance of aluminium in chemicals, I have quoted (between { }) their ADR number,[2] which is the United Nations four-digit code for the substance in question. The designation of organic chemicals listed in Parts M and N shall preferably be that according to the rules of IUAPC nomenclature.[3]

Excluded from the scope of this work are aluminium powder products, powder and granules whose properties and applications are not related to the applications of cast products, wrought semifinished products, rolled products, extruded products and so on. Also excluded are sintered aluminium powder composites as well as aluminized steel.

Reference

[1] Kaufman JB. Understanding wrought and cast aluminium alloys designations. [Chapter 3], ASM International, p. 23–37. https://doi.org/10.1361/iaat2000p023.

[1]The Aluminum Association, 1400 Crystal Drive Suite, 430 Arlington VA 22202.
[2]ADR, accord for dangerous goods by road.
[3]IUAPC, International Union of Pure and Applied Chemistry.

Index

Note: 'Page numbers followed by "f" indicate figures and "t" indicate tables'.

A

B

C

D

E

F

G

H

I

K

L

M

N

O

P

T

U

V

W

X

Y

Z

Corrosion of Aluminium SECOND EDITION

Christian Vargel

This revised and expanded new edition provides a global approach to the corrosion of aluminium, comprising the selection of alloys, design principles and service conditions

Corrosion of Aluminium: Second Edition highlights the practical and general aspects of the corrosion of aluminium alloys with many illustrations and references. It allows the reader who is not very familiar with aluminium to understand the metallurgical, chemical and physical aspects of aluminium alloys.

This second edition is fully updated and revised and expands on the first edition by adding hundreds of pages on new applications, new alloys, new technologies such as friction stir welding, twin roll casting, and new bibliographic references.

The book takes a practitioner approach, based on the expertise gained from the author's 50-year career in aluminium corrosion. This approach is most suitable for assessing the corrosion resistance of aluminium – an assessment which is one of the main conditions for the development of many uses of aluminium, including transport, construction, power transmission and packaging.

Key Features

- A comprehensive guide to over 100 years of related study with 2,000 bibliographic references
- Provides practical applications to the reader across many industries
- Lists the testing standards
- Valuable reference for both the beginner and the expert

Christian Vargel has over 50 years' experience in the corrosion and metallurgy of aluminium. He was chief engineer at Pechiney which was the European leader of wrought, extruded and cast aluminium products – where he primarily focused on corrosion of aluminium alloys, from a practical perspective. He surveyed and appraised numerous cases of in-service aluminium corrosion: building, transport, territory equipment, electrical and applications, and renewable energies such as solar, desalination and OTEC.

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