

WOODHEAD PUBLISHING IN MATERIALS



Surface engineering of light alloys

Aluminium, magnesium and
titanium alloys

Edited by Hanshan Dong



WP

Surface engineering of light alloys

Aluminium, magnesium and
titanium alloys

Edited by
Hanshan Dong



CRC Press
Boca Raton Boston New York Washington, DC

WOODHEAD PUBLISHING LIMITED
Oxford Cambridge New Delhi

Surface engineering of light alloys

Related titles:

Titanium alloys: modelling of microstructure, properties and applications
(ISBN 978-1-84569-375-6)

Computer-based modelling of material properties and microstructure is a very fast growing area of research and the use of titanium is growing rapidly in many applications. The book links the modelling of microstructure and properties to titanium. The first part reviews experimental techniques for modelling the microstructure and properties of titanium. A second group of chapters looks in depth at the physical models and a third group examines neural network models. The final section covers surface engineering products.

Surface coatings for protection against wear
(ISBN 978-1-85573-767-9)

This authoritative book presents an overview of the current state of research in, and applications for, wear protective coatings. It concentrates on the different types of surface technologies used for wear protective coatings. Each chapter provides an in-depth analysis of a particular type of surface coating, its properties, strengths and weaknesses in various applications. Each surface coating treatment examined includes case studies describing its performance in a specific application. *Surface coatings for protection against wear* is an invaluable reference resource for all engineers concerned with the latest developments in coatings technology.

Laser shock peening
(ISBN 978-1-85573-929-1)

Laser shock peening (LSP) is a relatively new surface treatment for metallic materials. LSP is a process to induce compressive residual stresses using shock waves generated by laser pulses. LSP can greatly improve the resistance of a material to crack initiation and propagation brought on by cyclic loading and fatigue. This book will be the first of its kind to consolidate scattered knowledge into one comprehensive volume. It describes the mechanisms of LSP and its substantial role in improving fatigue performance in terms of modification of microstructure, surface morphology, hardness and strength. In particular it describes numerical simulation techniques and procedures which can be adopted by engineers and research scientists to design, evaluate and optimise LSP processes in practical applications.

Details of these and other Woodhead Publishing materials books can be obtained by:

- visiting our web site at www.woodheadpublishing.com
- contacting Customer Services (e-mail: sales@woodheadpublishing.com;
fax: +44 (0) 1223 893694; tel.: +44 (0) 1223 891358 ext. 130; address:
Woodhead Publishing Limited, Abington Hall, Granta Park, Great Abington, Cambridge
CB21 6AH, UK)

If you would like to receive information on forthcoming titles, please send your address details to: Francis Dodds (address, tel. and fax as above; e-mail: francis.dodds@woodheadpublishing.com). Please confirm which subject areas you are interested in.

Published by Woodhead Publishing Limited, Abington Hall, Granta Park, Great Abington,
Cambridge CB21 6AH, UK
www.woodheadpublishing.com

Woodhead Publishing India Private Limited, G-2, Vardaan House, 7/28 Ansari Road,
Daryaganj, New Delhi – 110002, India
www.woodheadpublishingindia.com

Published in North America by CRC Press LLC, 6000 Broken Sound Parkway, NW,
Suite 300, Boca Raton, FL 33487, USA

First published 2010, Woodhead Publishing Limited and CRC Press LLC

© Woodhead Publishing Limited, 2010

The authors have asserted their moral rights.

This book contains information obtained from authentic and highly regarded sources. Reprinted material is quoted with permission, and sources are indicated. Reasonable efforts have been made to publish reliable data and information, but the authors and the publishers cannot assume responsibility for the validity of all materials. Neither the authors nor the publishers, nor anyone else associated with this publication, shall be liable for any loss, damage or liability directly or indirectly caused or alleged to be caused by this book.

Neither this book nor any part may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, microfilming and recording, or by any information storage or retrieval system, without permission in writing from Woodhead Publishing Limited.

The consent of Woodhead Publishing Limited does not extend to copying for general distribution, for promotion, for creating new works, or for resale. Specific permission must be obtained in writing from Woodhead Publishing Limited for such copying.

Trademark notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation, without intent to infringe.

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library.

Library of Congress Cataloging in Publication Data

A catalog record for this book is available from the Library of Congress.

Woodhead Publishing ISBN 978-1-84569-537-8 (book)

Woodhead Publishing ISBN 978-1-84569-945-1 (e-book)

CRC Press ISBN 978-1-4398-2984-4

CRC Press order number: N10172

The publishers' policy is to use permanent paper from mills that operate a sustainable forestry policy, and which has been manufactured from pulp which is processed using acid-free and elemental chlorine-free practices. Furthermore, the publishers ensure that the text paper and cover board used have met acceptable environmental accreditation standards.

Typeset by Replika Press Pvt Ltd, India

Printed by TJ International Limited, Padstow, Cornwall, UK

Contributor contact details

(* = main contact)

Editor and Chapter 3

H. Dong
School of Metallurgy and Materials
The University of Birmingham
Edgbaston
Birmingham B15 2TT
UK

E-mail: h.dong.20@bham.ac.uk

Chapter 2

C. Subramanian
Black Cat Blades Ltd
5604–59 Street
Edmonton
T6B 3C3, Alberta
Canada

E-mail: chinnia.subramanian@blackcatblades.com

Chapter 1

G.-L. Song
Chemical Sciences and Materials
Systems Laboratory
GM Global Research and
Development
General Motors Corporation
GM Mail Code: 480-106-400
30500 Mound Road
Warren, MI48090
USA

E-mail: guangling.song@gm.com

Chapter 4

A. Yerokhin
Research Centre in Surface
Engineering
Department of Engineering
Materials
The University of Sheffield
Sir Robert Hadfield Building
Mappin Street
Sheffield S1 3JD
UK

E-mail: a.yerokhin@sheffield.ac.uk

R. H. U. Khan*

School of Metallurgy and Materials
The University of Birmingham
Edgbaston
Birmingham B15 2TT
UK

E-mail: r.h.u.khan@bham.ac.uk

Chapter 5

B. L. Jiang

School of Materials, Science and
Engineering
Xi'an University of Technology
5 South Jinhua Road
Xi'an Shaanxi, 710048
China

E-mail: jiangbail@vip.163.com

Y. M. Wang*

School of Materials, Science and
Engineering
Harbin Institute of Technology
92 West Dazhi Street
Nan Gang District
Harbin, 150001
China

E-mail: wangyaming@hit.edu.cn

Chapter 6

C. Blawert* and B. Srinivasan
Corrosion and Surface Technology
Department
Magnesium Innovations Centre
(MagIC)

Institute of Materials Research
GKSS-Forschungszentrum
Geesthacht GmbH
D-21502, Geesthacht
Germany

E-mail: carsten.blawert@gkss.de
Bala.Srinivasan@gkss.de

Chapter 7

C. J. Li

State Key Laboratory for
Mechanical Behavior of
Materials
School of Materials Science and
Engineering
Xi'an Jiaotong University
Xi'an, Shaanxi, 710049
China

E-mail: licj@mail.xjtu.edu.cn

Chapter 8

W. Li

Shaanxi Key Laboratory of Friction
Welding Technologies
Northwestern Polytechnical
University
127 Youyi Xilu
Xi'an, 710072
Shaanxi
China

E-mail: liwy@nwpu.edu.cn

H. Liao*
University of Technology of
Belfort-Montbéliard
90010 Belfort cedex
France

E-mail: hanlin.liao@utbm.fr

H. Wang
School of Mechanical and
Materials Engineering
Jiujiang University
Jiujiang 332005
China

E-mail: wanght7610@163.com

Chapter 9

S. Abela
Department of Metallurgy and
Materials Engineering
University of Malta
Msida MSD06
Malta

E-mail: ssabel@eng.um.edu.mt

Chapter 10

F. Ashrafizadeh
Department of Materials
Engineering
Isfahan University of Technology
Isfahan 8415683111
Iran

E-mail: ashrafif@cc.iut.ac.ir

Chapter 11

Y. C. Xin and P. K. Chu*
Department of Physics and
Materials Science
City University of Hong Kong
Tat Chee Avenue
Kowloon
Hong Kong
China

E-mail: paul.chu@cityu.edu.hk

Chapter 12

T. N. Baker
Department of Mechanical
Engineering
University of Strathclyde
Glasgow G1 1XJ
UK

E-mail: neville.baker@strath.ac.uk

Chapter 13

J. C. Betts
Dept. of Metallurgy and Materials
Engineering
Faculty of Engineering
University of Malta
Msida MSD2080
Malta

E-mail: jbetts@eng.um.edu.mt

Chapter 14

X. Li*
School of Metallurgy and Materials
College of Engineering and
Physical Sciences
The University of Birmingham
Birmingham B15 2TT
UK

E-mail: x.li.1@bham.ac.uk

H. Dong
School of Metallurgy and Materials
The University of Birmingham
Edgbaston
Birmingham B15 2TT
UK

E-mail: h.dong.20@bham.ac.uk

Chapter 15

R. Y. Q. Fu
Department of Mechanical
Engineering
School of Engineering and Physical
Sciences
Heriot Watt University
Edinburgh EH14 4AS
UK

E-mail: R.Y.Fu@hw.ac.uk

Chapter 16

Dr J. Chen
School of Metallurgy and Materials
The University of Birmingham
Birmingham B15 2TT
UK

E-mail: j.chen.2@bham.ac.uk

Chapter 17

N. Huang* and Y. X. Leng
Key Lab of Advanced Materials
Technology
Ministry of Education
School of Materials Science and
Engineering
Southwest Jiaotong University
610031, China

E-mail: nhuang@263.net

P. D. Ding
School of Materials Science and
Engineering
Chongqing University
400030, China

Chapter 18

S. Shrestha*
Keronite International Ltd
Great Abington
Cambridge CB21 6GP
UK

E-mail: Suman.Shrestha@keronite.com

B. D. Dunn
European Space Agency
2200AG Noordwijk
The Netherlands

E-mail: Barrie.Dunn@esa.int

Light alloys, which encompass magnesium-, aluminium- and titanium-based materials, are the materials of choice for transport applications (such as aerospace, automotive and light rail) because of their low-density and high strength-to-weight ratio. Weight reduction in transport translates directly to fuel saving and emissions deduction, thus greatly contributing to ecologically and economically sustainable development. In addition, light alloys are attractive for some specific applications due to their unique properties. For example, outstanding biocompatibility makes titanium alloys the material of choice for body implants.

On the other hand, the relatively poor surface properties of light alloys represent a serious barrier to their wider application. For example, magnesium alloys have a reputation for extremely poor corrosion resistance in most environments; therefore, corrosion protection is essential for magnesium alloys in many applications (see Chapter 1). Further, light alloys are characterised, especially in sliding situations, by poor tribological properties manifested as: low load-bearing capacity and low resistance to abrasion mainly due to low hardness; and high adhesion tendency due to relatively high ductility and reactivity (Chapters 2 and 3). Therefore, light alloys are normally restricted to applications in which tribological performance is not critical.

Currently, however, there is a growing requirement to expand the use of titanium alloys to non-aerospace tribological applications. For example, it has long been the dream of designers to substitute titanium for steel components in racing-car engines to reduce the mass of valve trains, increase top speed and increase fuel efficiency. However, titanium alloys are characterised by poor wear behaviour (Chapter 3) and therefore it is impossible to use titanium components in valve train systems without proper surface engineering. More challenging examples include: water droplet erosion in longer titanium blades for high-efficiency low-pressure turbines, and adhesive wear of telescopic-action titanium tubes for aerial refuelling systems.

Equally, while aluminium alloys and magnesium alloys have found increasing application, particularly in aerospace and automotive industries, these alloys are susceptible to surface degradation. For instance, aluminium

alloys are used in the space industry in launchers, space stations and satellites because of their lightness, adequate corrosion resistance and good cryogenic properties. However, UV degradation and cold welding (or adhesion) in vacuum are concerns for successful long-term application of aluminium alloys and their finishes in space (Chapter 18). Similarly, the poor corrosion resistance of magnesium alloys in some service environments has limited further expansion of applications (Chapter 6).

Therefore, the clear and major challenge to surface engineering researchers and engineers, from both the scientific and technological viewpoints, is how to improve the surface properties of light alloys. During the past two decades, many surface engineering technologies have been developed to combat surface related failures such as corrosion, wear and fatigue of steels. The central problem is that surface engineering of light alloys is more difficult than it is for steels.

Firstly, there is no martensitic transformation hardening in light alloys: either there is no martensitic transformation – in magnesium alloys and aluminium alloys – or martensite in titanium alloys is not hard. Consequently, light alloys cannot be effectively hardened by induction hardening and, in most cases, it is difficult to provide a hardened subsurface for thin hard coatings. For this reason, although thin hard coatings *could* provide light alloys with improved tribological properties in terms of low-friction and wear, provided the applied load is low, the plastic deformation of the substrate, resulting from high contact stresses, gives rise to collapse of the coatings – the so-called ‘thin ice effect’.

Secondly, there is always an oxide film, thin or thick, on the surface of light alloys. These oxide films confer good corrosion resistance to aluminium alloys (Al_2O_3 film) and titanium alloys (TiO_2 film). However, such oxide films may cause difficult problems for surface engineering. They can reduce the bonding strength of surface coatings (for example, varying success of Ni plating) or retard diffusion of interstitial alloying elements during thermochemical treatment.

Thirdly, light alloys are very active and have strong affinity with oxygen, and therefore high purity gases must be used to prevent surface oxidation during thermochemical treatment (e.g. plasma nitriding of aluminium alloys).

Extensive research has been conducted to develop advanced surface engineering technologies for light alloys. However, surface engineering of light alloys has not yet been covered in a single book. Therefore, the objective of this book is to present a comprehensive review of the current status of surface engineering of light alloys. It can be divided into three sections, starting with a discussion on the surface degradation of light alloys (Chapters 1 to 3), followed by a portfolio of advanced surface engineering technologies applicable to light alloys (Chapters 4 to 15) and finishing with some application case studies (Chapters 16 to 18). Among these advanced surface engineering

technologies, plasma electrolytic oxidation treatment (Chapters 5 and 6) and ceramic conversion treatment (Chapter 14) are designed for light alloys.

The editor would like to take this opportunity to thank all the contributors, who are world-leading experts in their own research areas, for their willingness to share their time and knowledge. The contributions of Woodhead Publishing Limited, Rob Sitton, Lucy Cornwell and Francis Dodds are gratefully acknowledged. Finally, I must express my special gratitude to my family for their love, encouragement and support.

H. Dong

Contents

<i>Contributor contact details</i>	<i>xi</i>
------------------------------------	-----------

<i>Preface</i>	<i>xv</i>
----------------	-----------

Part I Surface degradation of light alloys

1	Corrosion behavior of magnesium alloys and protection techniques	3
	G.-L. SONG, General Motors Corporation, USA	
1.1	Introduction	3
1.2	Corrosion behavior of magnesium (Mg) alloys	3
1.3	Corrosion mitigation strategy	25
1.4	Future trends	31
1.5	Acknowledgements	32
1.6	References	33
2	Wear properties of aluminium-based alloys	40
	C. SUBRAMANIAN, Black Cat Blades Ltd, Canada	
2.1	Introduction	40
2.2	Classification of aluminium alloys	41
2.3	Composites	43
2.4	Introduction to wear	43
2.5	Sliding wear of aluminium alloys	45
2.6	Wear maps	52
2.7	Future trends	56
2.8	References	56
3	Tribological properties of titanium-based alloys	58
	H. DONG, University of Birmingham, UK	
3.1	Introduction	58
3.2	Wear behaviour of titanium alloys	60

3.3	Wear of titanium-aluminium intermetallics	71
3.4	Conclusions	76
3.5	Acknowledgements	77
3.6	References	77

Part II Surface engineering technologies for light alloys

4	Anodising of light alloys	83
	A. YEROKHIN, University of Sheffield, UK, and R. H. U. KHAN, University of Birmingham, UK	
4.1	Introduction	83
4.2	Formation of anodic films	84
4.3	Structural evolution of anodic films	90
4.4	Practical anodising processes	93
4.5	Pre-treatment processes	96
4.6	Anodising equipment	97
4.7	Post-treatment processes	99
4.8	Anodising magnesium	100
4.9	Anodising titanium	102
4.10	Future trends	105
4.11	References	107
5	Plasma electrolytic oxidation treatment of aluminium and titanium alloys	110
	B. L. JIANG, Xian University of Technology, China, and Y. M. WANG, Harbin Institute of Technology, China	
5.1	Introduction	110
5.2	Fundamentals of the PEO process	113
5.3	PEO power sources and process parameters	123
5.4	Properties and applications of PEO coatings	132
5.5	New process exploration	141
5.6	Future trends	145
5.7	Acknowledgements	145
5.8	References	146
6	Plasma electrolytic oxidation treatment of magnesium alloys	155
	C. BLAWERT and P. BALA SRINIVASAN, GKSS-Forschungszentrum Geesthacht GmbH, Geesthacht, Germany	
6.1	Introduction	155
6.2	Plasma electrolytic oxidation (PEO) treatments of magnesium (Mg) alloys	156
6.3	Microstructure of PEO-treated Mg alloys	158

6.4	Properties of PEO-treated Mg alloys	162
6.5	Recent developments in PEO treatments of Mg alloys	167
6.6	Industrial PEO processes and applications	178
6.7	Summary	180
6.8	References	180
7	Thermal spraying of light alloys C. J. Li, Xi'an Jiaotong University, China	184
7.1	Introduction	184
7.2	Characteristics of thermal spraying	185
7.3	Introduction to physics and chemistry of thermal spraying	192
7.4	Microstructure and properties of thermal spray coatings	210
7.5	Bonding between coating and substrate	219
7.6	Case studies	227
7.7	Future trends	230
7.8	Acknowledgements	232
7.9	References	232
8	Cold spraying of light alloys W. Li, Northwestern Polytechnical University, China, H. LIAO, University of Technology of Belfort-Montbéliard, France, and H. WANG, Jiujiang University, China	242
8.1	Introduction: General features of cold spraying (CS)	242
8.2	Potential applications of CS technique	245
8.3	CS of aluminium (Al) and its alloys	247
8.4	CS of titanium (Ti) and its alloys	274
8.5	Surface modification of magnesium alloys by CS	287
8.6	Future trends	289
8.7	References	290
9	Physical vapour deposition of magnesium alloys S. ABELA, University of Malta, Malta	294
9.1	Introduction	294
9.2	Surface engineering of magnesium alloys	295
9.3	Ion beam assisted deposition (IBAD) and reactive ion beam assisted deposition (RIBAD)	298
9.4	Effects of ion bombardment	302
9.5	RIBAD deposition of titanium nitride (TiN) on magnesium alloys	307
9.6	Sliding wear and aqueous corrosion of Mg alloys	309
9.7	Conclusion	319
9.8	References	320

10	Plasma-assisted surface treatment of aluminium alloys to combat wear	323
	F. ASHRAFIZADEH, Isfahan University of Technology, Iran	
10.1	Introduction	323
10.2	Effect of plasma on surface oxide film	328
10.3	Plasma nitriding of Al alloys	331
10.4	Physical vapour deposition (PVD) of aluminium alloys	335
10.5	Duplex surface treatment	348
10.6	Load bearing capacity and interface design	351
10.7	Summary	358
10.8	References	359
11	Plasma immersion ion implantation (PIII) of light alloys	362
	Y. C. XIN and P. K. CHU, City University of Hong Kong, China	
11.1	Introduction	362
11.2	Processes and advantages of plasma immersion ion implantation (PIII)	363
11.3	PIII surface modification of titanium (Ti) alloys	369
11.4	PIII surface modification of magnesium (Mg) alloys	375
11.5	PIII surface modification of aluminum (Al) alloys	387
11.6	Future trends	392
11.7	Sources of further information and advice	393
11.8	References	393
12	Laser surface modification of titanium alloys	398
	T. N. BAKER, University of Strathclyde, UK	
12.1	Introduction	398
12.2	Lasers used in surface engineering	399
12.3	Laser surface modification methods	400
12.4	Laser processing conditions for surface engineering	405
12.5	Laser surface melting and cladding	410
12.6	Laser surface alloying	413
12.7	Effect of laser surface modification on properties	419
12.8	Summary	433
12.9	Acknowledgements	433
12.10	Sources of further information and advice	434
12.11	References	434
13	Laser surface modification of aluminium and magnesium alloys	444
	J. C. BETTS, University of Malta, Malta	
13.1	Introduction	444

13.2	General considerations on the laser processing of light alloys	445
13.3	Laser surface remelting of light alloys	448
13.4	Laser surface alloying of light alloys	454
13.5	Laser surface cladding of light alloys	458
13.6	Laser surface particle composite fabrication processes	461
13.7	Laser shock treatment of Al alloys	465
13.8	Future trends	467
13.9	Sources of further information and advice	468
13.10	References	469
13.11	Bibliography	473
14	Ceramic conversion treatment of titanium-based materials X. LI and H. DONG, University of Birmingham, UK	475
14.1	Introduction	475
14.2	Ceramic conversion treatment (CCT) of titanium and titanium alloys	477
14.3	CCT for TiAl intermetallics	487
14.4	CCT of TiNi shape memory alloys	491
14.5	Summary and conclusions	496
14.6	Future trends	496
14.7	Acknowledgements	497
14.8	References	498
15	Duplex surface treatments of light alloys R. Y. Q. FU, Heriot Watt University, UK	501
15.1	Introduction	501
15.2	Duplex surface treatment of titanium (Ti) alloys	504
15.3	Load bearing capacity of duplex surface treatments	506
15.4	Tribological properties of duplex surface treatments	511
15.5	Erosion performance of duplex surface treatments	522
15.6	Duplex surface treatment based on diamond-like carbon (DLC) or titanium nitride (TiN) films with plasma nitriding	523
15.7	Duplex surface coating with oxygen diffusion inlayer	527
15.8	Other duplex surface treatments for titanium alloys	530
15.9	Duplex surface treatment of aluminium (Al) alloys	532
15.10	Summary	539
15.11	References	540