

TCSTE

Contributions of Surface Engineering to Modern Manufacturing and Remanufacturing

**3rd International Conference
on Surface Engineering**

October 10-13, 2002

Chengdu

By

Editor-in-chief Siwei Zhang

Editors Zhongrong Zhou, Jiajun Liu, Minhao Zhu



Southwest Jiaotong University Press

Chengdu, P. R. China

图书在版编目 (C I P) 数据

表面工程对现代制造及再制造业的贡献: 第三届表面工程国际会议论文集 / 张嗣伟主编. —成都: 西南交通大学出版社, 2002.10

ISBN 7-81057-661-5

I. 表... II. 张... III. 金属表面保护 — 国际学术会议 — 文集 — 英文 IV. TG17-53

中国版本图书馆 CIP 数据核字 (2002) 第 065574 号

第三届表面工程国际会议论文集
3rd International Conference on Surface Engineering
表面工程对现代制造及再制造业的贡献
Contributions of Surface Engineering to
Modern Manufacturing and Remanufacturing

张嗣伟 主编

*

出版人 宋绍南

责任编辑 祁素玲

封面设计 肖勤

西南交通大学出版社出版发行

(成都市二环路北一段 111 号 邮政编码: 610031 发行科电话: 87600564)

<http://press.swjtu.edu.cn>

E-mail: cbsxx@swjtu.edu.cn

西南冶金地质印刷厂印刷

*

开本: 880mm×1230mm 1/16 印张: 38.75

字数: 1188 千字 印数: 1—600 册

2002 年 10 月第 1 版 2002 年 10 月第 1 次印刷

ISBN 7-81057-661-5/TG · 293

定价: 180.00 元

MAIN SPONSORS

- ◇ **CHINESE NATIONAL NATURAL SCIENCE FOUNDATION**
- ◇ **K. C. WONG EDUCATION FOUNDATION, HONG KONG**

SUPPORTING ORGANIZATIONS

- ◇ **Division of Mechanical and Vehicle Engineering of Chinese Academy of Engineering**
- ◇ **Chinese Mechanical Engineering Society (Tribology, Materials and Heat Treatment Institution)**
- ◇ **International Federation for Heat Treatment and Surface Engineering**
- ◇ **Institute of Mechanical Engineering, U. K.**
- ◇ **Japan Society of Mechanical Engineering**
- ◇ **Romanian Society of Mechanical Engineering**

Conference Chairman

Xu Bin-Shi (Armored Force Engineering Institute, CHINA)

Conference Cochairman

Thome Bell (University of Birmingham, U. K.)

Organization Chairman

Zhou Zhong-Rong (Southwest Jiaotong University, China)

Program Chairman

Liu Jia-Jun (Tsinghua University, CHINA)

Consultative Committee

Ding Chuan-Xian (Shanghai Institute of Ceramics, Chinese Academy of Sciences, CHINA)

Ding Pei-Fan (Chinese Mechanical Engineering Society, CHINA)

Fukuhisa Matsuda (Osaka University, JAPAN)

Hai Jin-Tao (Chinese Academy of Machinery Science and Engineering, CHINA)

H. Peter Jost (Internation Tribology Council, U. K.)

Li Jian (Ministry of science and technology, CHINA)

Lian Yuan-Jian (Chinese Mechanical Engineering Society, CHINA)

Shen Zhi-Yun (Southwest Jiaotong University, CHINA)

Shi Chang-Xu (Chinese Academy of Engineering, CHINA)

Song Tian-Hu (Chinese Mechanical Engineering Society, CHINA)

Sun Da-Yong (China Association Science and Technology, CHINA)

Tu Ming-Jing (Sichuan University, CHINA)

Wladyslaw Wlosiński (Warsaw University of Technology, POLAND)

Xue Qun-Ji (Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, CHINA)

Jean-Marie George (Ecole Centrale de Lyon, FRANCE)

Academic Committee

Ali Erdemir (Energy Technology Division Argonne National Laboratory, U. S. A.)

Gao Wan-Zheng (Wuhan Research Institute of Materials Protection, CHINA)

He Jia-Wen (Xi'an Jiaotong University, CHINA)

Ian M. Hutchings (University of Cambridge, U. K.)

Kenneth Holmberg (VTT Technical Research Center of FINLAND)

Leo Vincent (Ecole Centrale de Lyon, FRANCE)

Liu Jia-Jun (Tsinghua University, CHINA)

Luo Wei-Li (Shanghai Research Institute of Materials, CHINA)

Ma Shi-Ning (Armored Force Engineering Institute, CHINA)

N.K. Myshkin (Belarus National Academy of Sciences, BELARUS)

Shoji Miyake (Osaka University, JAPAN)

Wang Cheng-Tao (Shanghai Jiaotong University, CHINA)

Wang Tian-Min (Beijing University of Aeronautics and Astronautics, CHINA)

Wen Shi-Zhu (Tsinghua University, CHINA)

Xie You-Bai (Xi'an Jiaotong University, CHINA)
Xu Ke-Wei (Xi'an Jiaotong University, CHINA)
Zhang Si-Wei (University of Petroleum, CHINA)

Organizing Committee

An Gui-Hua (Chinese Academy of Machinery Science and Engineering, CHINA)
Andrzej Kolasa (Warsaw University of Technology, POLAND)
Diao Dong-Feng (Xi'an Jiaotong University, CHINA)
Ge Shi-Rong (China University of Mining and Technology, CHINA)
Hong Liang (University of Alaska Fairbanks, U. S. A.)
Huang Nan (Southwest Jiaotong University, CHINA)
Li Chang-Jiu (Xi'an Jiaotong University, CHINA)
Li Jian (Wuhan Research Institute of Materials Protection, CHINA)
Li Ren-Han (Chinese Academy of Engineering, CHINA)
Lin An (Wuhan Research Institute of Materials Protection, CHINA)
Liu Wei-Min (Lanzhou Institute of Chemical Physics, Chinese Academy of Sciences, CHINA)
Lu Zhong-Zhou (Wuhan Research Institute of Materials Protection, CHINA)
Luo Jian-Bin (Tsinghua University, CHINA)
Ma Shi-Ning (Armored Force Engineering Institute, CHINA)
Peng Zhu Wang (University of Cambridge, U. K.)
Ronghua Wei (Southwest Research Institute, U.S.A.)
Zhou Zhong-Rong (Southwest Jiaotong University, CHINA)
Zhu Sheng (Armored Force Engineering Institute, CHINA)

Editor-in-chief

Zhang Si-Wei (University of Petroleum, CHINA)

Editors

Zhou Zhong-Rong (Southwest Jiaotong University, CHINA)
Liu Jia-Jun (Tsinghua University, CHINA)
Zhu Min-Hao (Southwest Jiaotong University, CHINA)

General Secretary

Zhu Min-Hao (Southwest Jiaotong University, CHINA)

Preface

Along with the rapid development of science and technology on a global scale, the Surface Engineering is growing fast and is becoming even more important than it has been in the past. However, it will face the new developing opportunities and severe challenges, such as environment, energy and sustainability. As one of the series of major surface engineering international conferences in China, the 3rd International Conference on Surface Engineering is just held in Chengdu, a famous historic city in China, against this background. The main theme of the conference is a major contribution towards surface engineering to the modern manufacturing and remanufacturing. The major aim of this conference is facilitating the exchange of expert knowledge and experiences from all over the world and attempting to emphasize the bridge between research and application.

This set of conference proceedings contains valuable contributions by many experts in the surface engineering profession. There are altogether 111 selected papers and 17 invited lectures in this volume, of which 59 papers are from about 15 countries in the world and 69 papers from China. They fall essentially into the following topics, according to which the technical sessions will be mainly conducted:

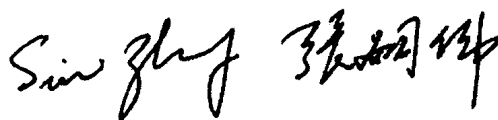
- Thermal Spraying Technology
- Electrodeposition and Electroless Deposition Technology
- Vapour deposition technology
- Diffusion treatment technology
- High energy beam modifications
- Surface engineering in biomaterials
- Nano-surface engineering and nanotribology
- Tribology

These lectures and papers reflect the recent achievements of research and development in the areas of surface engineering, the high quality of which will further promote the development of this science and technology.

Some members of the Program Committee helped greatly to review the technical papers and to offer valuable suggestions. To them, I want to express my heartfelt gratitude.

Wishing every success to the conference and to all participants.

Editor-in-Chief



Zhang Si-Wei, Professor

July 12, 2002

CONTENTS

Invited Papers

Low Temperature Plasma Nitriding and Carburising of Austenitic Stainless Steel for Combined Wear, Corrosion and Fatigue Properties <i>T Bell, X Li, H Dong</i>	3
Advanced Surface Engineering and Its Progress <i>Binshi Xu, Sheng Zhu, Shining Ma, Xiubing Liang</i>	11
Tribology of Thin Surface Coatings <i>Kenneth Holmberg, Helena Ronkainen, Allan Matthews</i>	17
An Optical Method for Assessing Scratch Damage in Bulk Materials and Coatings <i>I. M. Hutchings, P. Z. Wang, G. C. Parry</i>	24
Surface Science in Tribology <i>Y. Z. Hu, S. Z. Wen</i>	30
Contact Damage in Assemblies <i>L. Vincent, V. Fridrici, S. Fouvry, Ph. Kapsa</i>	34
Tribological Coatings for Space Mechanism Applications <i>Qunji Xue, Jiayi Sun</i>	42
Plasma-hardfaced Chromium Protective Coatings-effect of Ceramic Reinforcement on Their Wettability by Glass <i>Wladyslaw Wlosinski, Tomasz Chmielewski</i>	48
Spatial Characterization of Engineering Surface <i>N.K. Myshkin, A. Ya. Grigoriev</i>	54
Preparation of High Quality Perovskite Oxide Films by ECR Plasma Sputtering and Millimeter-wave Irradiation <i>Shoji Miyake</i>	62
Novel Lubrication Engineering for Rigid Magnetic Recording Disk <i>Jun Zhang</i>	67
Surface Reflectance Analyzers—A Surface Inspection Tool for Tribology Research <i>G. H. Vurens</i>	71
Nanocoatings Tribology <i>D. F. Diao, F. Iwata, S. Hirono, S. Umemura, Y. B. Xie</i>	77
Plasma and Ion Beam Surface Engineering Research at Southwest Research Institute <i>Ronghua Wei, James Arps</i>	82
Laser Manufacturing Technology and Its Application on the Surface Engineering <i>Tiechuan Zuo, Kai Chen</i>	87
Analysis on Causes of 244.5mm-350t Elevator Fracture <i>Shuanlu Lu, Heling Li</i>	91
Tribological Behavior in Chemical-mechanical Planarization <i>H. Liang, J. Li, R. Erck</i>	95

Thermal Spraying Technology

The Effect of Processing Variables on Deposition Characteristics of Aluminium by Cold Gas Dynamic Spraying <i>D. Zhang, P.H. Shipway, D.G. McCartney</i>	105
Processing and Properties of Glass Composite Coatings with Enhanced Wear Resistance <i>Y Bao, T Zhang, Z Qiu, D T Gawne</i>	111
Study of High Temperature Corrosion Properties about Several Arc Sprayed Coatings <i>Q. Liu, S. N. Ma</i>	116
Effect of a Blasting Angle and Spray Parameters on the Bonding Strength between Arc Sprayed FeCrAl Coatings and 1045 Grade Steel Substrates <i>Guimin Liu, Binshi Xu, Lili Ma, Krzysztof J. Kurzydowski</i>	119
Hardfacing by Plasma Transferred Arc in Manufacturing and Remanufacturing Processes <i>Andrzej Kolasa</i>	123
Thermal Sprayed Intermetallic Alloy-coatings and Their Carburization Resistance at High Temperature <i>Y. Wang, W. Chen, Yuxiang Lu, L. Benum</i>	128
Design and Simulation of Thermal Barrier Coatings for High Temperature Engine Nozzles <i>Jin Zhang, Hulin Wu, Qi Yu</i>	134
Effect of Post Heat Treatment and Sealing on Erosion Resistance of Several Thermal Sprayed Coatings <i>B. Q. Wang</i>	138
Friction and Wear Characteristics of Plasma-sprayed WC Coatings against GCr15 Steel <i>Y. Chen, Y. Z. Zhang, H. B. Xiao, B. Shangguan, X. S. Tie, L. M. Sun</i>	144
Investigation of Multiple Strengthening Mechanism in Pure Titanium <i>Jianbin Zhang, Genshun Ji, Ding Fan, Jianlin Xu</i>	147
Mechanical Properties and Friction Behavior of Thermal Spray PEEK Coatings <i>Hanlin Liao, Jiangfeng Li, Simpin Laurence, Coddet Christian</i>	150
Study on Wear Resistance of Three Kinds of Thermal Sprayed Coating <i>D. L. Duan, S. Li, X. H. Duan, S. Z. Li</i>	157
Effect of Spray Conditions on the Microstructure and Properties of Micro-plasma Sprayed Cu Coating <i>B. Sun, C.J. Li, M. Wang, F. Han, T. Wu</i>	161
Research of High Velocity Oxygen-air Fuel Spray <i>Hangong Wang, Bailin Zha</i>	166

- Factors Influencing the Adhesive Strength of HVOF Sprayed Coatings
Y. Y. Wang, C. J. Li, T. Wu, A. Ohmori 169
- Microstructure and Sliding Wear Behaviors of Fe-Al Coatings Produced by High Velocity Arc Spraying
Zixin Zhu, Binshi Xu, Shining Ma, Wei Zhang, Zeyu Du 174
- Effect of Surface Coatings on the Mechanical Properties of Type 316 Austenitic Stainless Steel
Guimin Liu, Binshi Xu, Lili Ma, Krzysztof J. Kurzydowski 178
- Effect of Optical System Design on Signal Characteristics and Level during the Simultaneous Measurement of State Parameters of Thermally Sprayed Particle
Tao Wu, Chengxin Li, Changjiu Li 182
- Hot Corrosion Resistance of NiCr Based Cermet Coatings for the Protection of Boiler Heat Exchanger Tubes
Zhangxiong Ding, Zhenlin Pei, Wangbin Zhan, Qun Wang 188
- The Proposal of Determining Quantitative Synergism in Surface Engineering
Tadeusz Burakowski 193
- Electrodeposition and Electroless Deposition Technology**
- Development of Electrodeposition of Nickel Polymer Composite by the Zwitterionic Surfactant
Z. Abdel Hamid, A. M. A. Omar 201
- Development of Multi-layer Ni-Cr Coating for High Decorative and Corrosion Resistant Applications
Joon-Kyun Lee, Wan-Zhen Gao, Sang-Gweon Kim, Zu-Guo Mao, Myung-Ken Han 204
- Study on the Corrosion Resistance and the Wear Resistance of Electroless Nickel Plating of Magnesium Alloy
Guolu Li, Fenggang Bian, Jinhai Liu, Gengsheng Liu, Jiajun Liu, Kunlin Wang 210
- Enhancement the Properties of Austenitic Stainless Steel by Nickel Diffusion Coatings
Z. A. Hamid, M. A. Abbas, N. Gomaa 214
- Ni-SiC Composite Coating Prepared in Centrifugal Field
Guangjie Shao, Xiujuan Qin, Haiyan Wang, Jian Hao, Tianfu Jing, Mei Yao 218
- Research on the Effect of RE on Electroless Nickel-phosphor Plating
Yisheng Chen, Yong Wang, Huizhou Liu 222
- Nano-surface Engineering and Nano-tribology**
- Preparation and Characterization of Nano-crystalline Diamond Films on Glass Substrate
F. X. Lu, W. B. Yang, Z. L. Liu, W. Z. Tang, Y. M. Tong 229
- Analysis of Changes in DLC Coating during Friction by AFM
S. A. Chizhik, H. S. Ahn, Zhuang Yan, S. V. Korotkevich 233
- Fabrication and Nanotribological Properties of Molecular Deposition (MD) Films Assembly with PDDA/TiO₂/PDDA/Graphite Oxides Nanocomposition
Dapeng Feng, Deguo Wang, Huiqing Lan, Siwei Zhang 239
- Surface Modification of Nanoparticles by Plasma Polymerization
William J. van Ooij, Donglu Shi, Vesselin Shanov ... 242
- Commercialization of Nanostructured Feedstock Materials for the Thermal Spray Industry
Xinqing Ma, James C. Hsiao, David E. Reisner, Guanbao Zhang, Huaming Zhao, Winhua Xu 247
- Development and Implementation of Thermal Spray Nanocoatings Using Commercial Nanostructured Feedstock Products
T. D. Xiao, David E. Reisner 252
- Modification of Metal Surface with Carbon Nanotubes
X. H. Chen, F. Q. Cheng, L. P. Zhou, S. L. Li 256
- The Surface Chemical Modifications of Nanotitanium Oxide and Its Applications in Coating
An Lin, Xuequn Cheng 260
- Effect of CeO₂ and Nanoscale WC on Wear Resistance of Laser Cladding WC Composite Coatings
Huahui Chen, Fanzi Zeng, Caiyun Xu, Xiangdong Ma, Jingxin Qu, Jiajun Liu 262
- Preparation of Diamond Film by Hot Filament Chemical Vapor Deposition and Nucleation Action of Carbon Nanotube
C. Wang, D. M. Zhuang, G. Zhang, Y.Q. Hou, J. J. Liu 266
- Plasma Spray Nano-structured Oxid Ceramic Coatings
Soo Wahn Lee, Seung Ho Kim, Se Hun Chang, Yi Zeng, Takafumi Kusunose, Koichi Niihara 270
- Microstructure and Wear Characteristics of Brush-plated n-Al₂O₃P/Ni Composite Coating
Binshi Xu, Shiyun Dong, Shining Ma, Hongmei Wang 273
- Characterisation of Thin Film Adhesion with the Nano-scratch Tester(NST)
Nicholas X. Randall, Richard Consiglio 276
- Surface Force Apparatus (SFA) Studies of Frictional Properties of C₆₀ Copolymer Films
Jing Zhang, Tao Zhang, Hui Wang, Yuanzhong Hu, Lan Huang 281
- Vapour Deposition Technology**
- Problems of Modern Surface Engineering Technology Implementation
Adam Mazurkiewicz 287
- Adhesion of Coatings with High Hardness
M. Kupczyk 294

- In-situ Reaction Deposition of Alumina Ceramic Film by Laser-induced Vacuum Arc
Haoqun Li, Tianmin Shao, Dao Se, Weidong Yuan, Darong Chen 299
- Mechanical Properties of Diamond-like Carbon (DLC) Films Synthesized by Pulsed Vacuum Arc Plasma Deposition
Y. X. Leng, N. Huang, H. Sun, J. Y. Chen, M. H. Zhu, X. Y. Shi, S. Y. Qiu 302
- Pack Deposition of Oxidation Resistant Silicide and Aluminide Coatings on γ -TiAl
Z. D. Xiang, S. Rose, P. K. Datta 306
- The Effect of Addition Nd on Magneto-optical of Tb-Fe-Co Film
Xiyang Zhang, Shijie Zhou, Zhinong Liu, Bin Zou ... 311
- The Comparative Investigations of Durability of Superhard Coatings Deposited on Cutting Tool Edges
M. Kupczyk, W. Misiak 314
- Study on Modification of Boron Carbide Particles for Reinforced Copper Matrix Composites
Guolu Li, Jinhai Liu, Xinchang Jiang, Xiaoming Cao, Ming Wen 319
- New Technologies of Surface Engineering in the Area of Industrial Implementation
Adam Mazurkiewicz, Jerzy Smolik, Jan Walkowicz 323
- Characterization of an HFVCD Boron-doped Sub-microcrystalline Diamond Film
Xuemin Li, Zhen Zhang, Darong Chen, Jiadao Wang 329
- Composite Layers Produced by Combined Nitriding and PACVD Processes under Glow Discharge Conditions
T. Wierzchoń, J. R. Sobiecki, P. Mañowski, J. Trojanowski 333
- Adhesion of Chromium Films Deposited by D. C. Magnetron Sputtering to Zr-2 Substrate
H. Y. Fan, W. Li, B. L. Shen, Z. H. Tang, W. X. Xing, S. H. Ying 338
- Investigations of Brittleness of c-BN+ h-BN Coatings
M. Kupczyk, A. Lejwoda, K. Jozwiak 342
- The Effect of Negative Bias on Composite Si-B-N Thin Films Deposited by Radio-frequency PCVD Method
Chengbiao Wang, Junfeng Yu, Hua Meng 348
- Individual Coatings for Cutting Tools
Stefan Esser 352
- High Energy Beam Modifications**
- Low-temperature Tribological Properties of Solid Lubricating Coatings
Guizhen H. Xu, Jonah H. Lee, Hong Liang 357
- Low-energy Ion Implantation at Grazing Incidence
A.A. Dzburakhalov 363
- Tribological Characteristics of Fe-implanted 2024 Aluminium Alloy
Jianmin Chen, Aimin Zhang, Zongxin Mu, Jinjun Lu, Aimin Wu 366
- High-current Pulsed Electron Beam: Enhanced Diffusion Effects and Wear Resistance Improvement
Chuang Dong, Aimin Wu, Shengzhi Hao, Zhenmin Liu, Aimin Zhang, Tao Xu, Jin Xu, Qiyue Liu, Zhongrong Zhou 370
- Friction and Wear Characteristics of Laser Clad Copper Matrix in situ Composite Coating
Shiyun Dong, Binshi Xu, Jiecai Han, Shanyi Du 376
- Surface Modification of UHMWPE by Nitrogen Implantation
W. Shi, H. Dong 379
- Corrosion Resistance of Plasma-based Low-energy Nitrogen Ion Implanted Austenitic Stainless Steel
M. K. Lei, X. M. Zhu 384
- Nitriding of Mullite/Al-4.5 Cu Composite by Plasma Ion Implantation
W. Li, X. J. Zhang, Y. X. Yin, X. Y. Dai, H. Y. Fan, H. H. Tong 388
- Fretting Wear Behavior of D2 Die Steel after Surface Modification by High Current Pulsed Electron Beam
Aimin Wu, Hanwei Liu, Jianxin Zou, Zhongrong Zhou, Chuang Dong 392
- Enhanced Wear Resistance of High-speed Steel by Pulsed Electron-beam Melting
Yu. Ivanov, W. Matz, V. Rotshtein, R. Guenzel, N. Shevchenko 397
- Study of the Surface Layers Created on Aluminium-silicon Alloy by Laser Treatment under Cryogenic Conditions
Waldemar Serbiński, Jean Marc Olive, Tadeusz Wierzchoń, Jarosław Rudnicki 403
- Diffusion Treatments**
- Surface Integrities of Radical Nitrided Maraging Steel
N. Kawagoishi, K. Morino, Q. Y. Wang, Y. Yan, E. Kondo, K. Fukada 409
- Plasma Nitriding Technology Using Dielectric Barrier Discharge at Atmospheric Pressure
Li Yan, Xinhe Zhu, Yan Qin, Jiujun Xu, Yuzhou Gao 413
- Effect of Aluminum Contents on the Coating Structures and Dross Formation of Hot-dip Galvanizing Processes
Saher Shawki, Z. Abdel Hamid 417
- Saving Cost with Epsilon Nitrocarburising
A. Malas, P. F. Stratton, K. Bennett 421
- Non-equilibrium Thermodynamics of Plasma-nitriding of Tantalum
D Y Zhang, F Li, L Wen, L P Xu, W J Zeng, D P Lu, Z Zhou 426
- Study of the Properties and Microstructure of S-N-C Plasmas Composite Treatment Layer on the Surface of Cr12MoV
Xiaochun Wu, Shuangke Zhang, Yongan Min, Luoping Xu 429
- Effect of Plasma Nitriding on Thermal Fatigue Behavior of H13 Steel
Xiaochun Wu, Wenyi Peng, Yongan Min, Luoping Xu 434

- Changing Regularity of Structure and Phase of HDA-steel under Diffusion Treatment
S. X. Yu, Y. Xia, M. Yao 439
- The Tribological Properties of Ion Sulfurized Die-steel under Dry Sliding Condition
Haidou Wang, Daming Zhuang, Kunlin Wang, Jiajun Liu 442
- Development of Duplex Plasma Surface Treatment Technology for Improvement of Properties of Die Casting Mold
Sang-Gweon Kim, Wan-Zhen Gao, Ki-Tae Kim, Guo-Wei Lin, Woon-Jae Jung, Hui Zheng, Hha Ni, Xiao-Lin Liu 446
- ### Surface Engineering in Biomaterials
- State-of-the-art of Surface Modification of Biomaterials Applied for Cardiovascular Devices
N. Huang, P. Yang, Y. X. Leng, J. Y. Chen, H. Sun, J. Wang, G. J. Wan 453
- Surface Engineering of Prosthetic Bearing Surfaces
H. Dong 457
- Ti Based Coatings on Stainless Steel for Bone Integrated Implants
S. Mukherjee, M.-T. Pham, M. F. Maitz 465
- Effect of Surface Hydroxyl Groups and Surface Energy of Titanium on Adsorption of Bovine Serum Albumin
B. Feng, J. Weng, B. C. Yang, S. X. Qu, H. S. Fan, J.Y. Chen, X. D. Zhang 469
- Behavior of Platelet Adhesion on Tantalum Containing Ti-O / Ti-N Film Synthesized by Magnetron Sputtering Deposition
J. Y. Chen, N. Huang, P. Yang, Y. X. Leng 473
- Study on the Subsonically Thermal Sprayed Coating of Hydroxyapatite
Muqin Li, Dashan Shang, Hongtao Chen, Chen Ma 478
- Plasma Surface Modification of Medical Polyurethane for Antithrombogenicity
J. Wang, N. Huang, S. Hong, P. Yang, Y. X. Leng, J. Y. Chen, G. J. Wan 481
- Investigation of the Platelets Adhesion Behavior on Ti-O Film Deposited by Plasma Immersion Ion Implantation and Deposition
G. J. Wan, N. Huang, Y.X. Leng, P. Yang, J. Y. Chen, H. Sun, J. Wang 485
- A Study on the Hydroxylapatite Coatings on Titanium Substrate Prepared by Detonative Method
Youlong Zhou, Nan Huang, Jichun Zhang, Xuebin Guo 488
- ### Tribology
- Technology of Flat Surfaces Lapping
A. Barylski 495
- A New Approach to Modeling Material Removal and Chemical-mechanical Synergy in Chemical Mechanical Polishing
Yongwu Zhao, L. Chang, S. H. Kim 499
- Effect of Surface Roughness of Self-mated Alumina on Friction and Wear in Lubricated Reciprocating Sliding Contact
L. Fang, U. Dulas, K.-H. Zum Gahr 505
- Study on the Combined Processes of Sliding and Creep of UHMWPE
Jun Xue, Jian Li, Meng Hua 512
- Fractal Analysis on 3-D Surfaces of C.G. Irons under Dry Sliding
Yongzhen Zhang, Leming Sun, Weimin Liu, Jun Zhu, Bao Shangguan, Yue Chen 516
- Enhanced Wear Performance of Ultra High Molecular Weight Polyethylene Crosslinked by Organosilane
Xiaolin Xie, Chakyin Tang, Xuecheng Wu, Robert K. Y. Li, Hang Wu 520
- A New Phenomenon: Periodical Valleys of Friction Coefficients and Wear Plateau of Thermoplastic Polymer
G. N. Dong, J. Li, Y. B. Xie 524
- Thermal-mechanical Finite Element Analysis of the Rolling-sliding Contact with Inclusion
B. K. Wang, G. N. Dong, Y. B. Xie 528
- Debris Group Theory and Its Latest Development in Ferrography
Hangjun Shi, Yubin Liu, Liucun Xu 532
- An Approximate Method for Determining Performance of a Mechanical Face Seal with Circular Deep Grooves
Xudong Peng, Yusui Mai, Weiming Zhong, Hongju Yu 534
- An Investigation of Rail Corrugation with Tribo-fatigue Method
A. V. Bogdanovich, Q. Y. Liu, Z. R. Zhou, L. A. Sosnovskiy 538
- A Tribological Method for Evaluating Mechanical Properties of Material Surface
S. Li, H. W. Liu, R. X. Wang, D. L. Duan, S. Z. Li 541
- Wear Performance of Ultra High Molecular Weight Polyethylene/Quartz Composites
Xiaolin Xie, Chakyin Tang, Xuecheng Wu, Robert K. Y. Li, Hang Wu 546
- Experimental Study of Spiral Groove Upstream Pumping Mechanical Seals
Danmei Hu, Xudong Peng, Mumin Hao, Huixia Yang 551
- The Preparation and Application of Magnetic Fluids Used in Ferrographic Analysis
Yubin Liu, Tonggang Liu, Zhiyi Yang 554
- Study on Tribological Characteristics of Pseudoelastic TiNi Alloys
Xuewen Huang, Guangneng Dong, Hui Wang, Zhongrong Zhou, Youbai Xie 558
- Three-dimensional Thermohydrodynamic Analysis of Circular Journal Bearing
Y. L. Fu, X. Z. Ma, J. Zhu 562

Composite Fretting Behaviour of Aluminum-lithium Alloy against Bearing Ball

M. H. Zhu, Z. R. Zhou, Ph. Kapsa, L. Vincent 566

Preparation and Tribological Behaviors of Phosphor-nitrogen Modified Rapeseed Oil as Biodegradable Lube Additive in Vegetable Oil

Boshui Chen, Jianhua Fang, Jiu Wang, Lin Dong, Weijiu Huang 573

A Study on the Fractal Behavior of Worn Surfaces of Zinc Oxide Whisker/Natural Rubber-styrene Butadiene Rubber-butadiene Rubber Composites

Z. W. Zhou, L. S. Chu, S. K. Liu, L. X. Gu 577

Investigation on the Tribological Properties of Water-soluble Imidazoline Borate

Weijiu Huang, Changhua Du, Ying Zeng 581

Others

Influence of Surface Hardened Treatments on Fatigue Limits of 30CrMnSiNi2A Steel

Yukai Gao, Feng Lu, Mei Yao, Yuanfa Yin 587

Application of Water Based Inorganic Zinc Silicate Anti-corrosive Coatings on Steel Structure

Shining Ma, Rui Yan, Binshi Xu, Hang Wu 591

Corrosion Resistance of Metals Coated with Organofunctional Silanes

W.J. van Ooij, Danqing Zhu 594

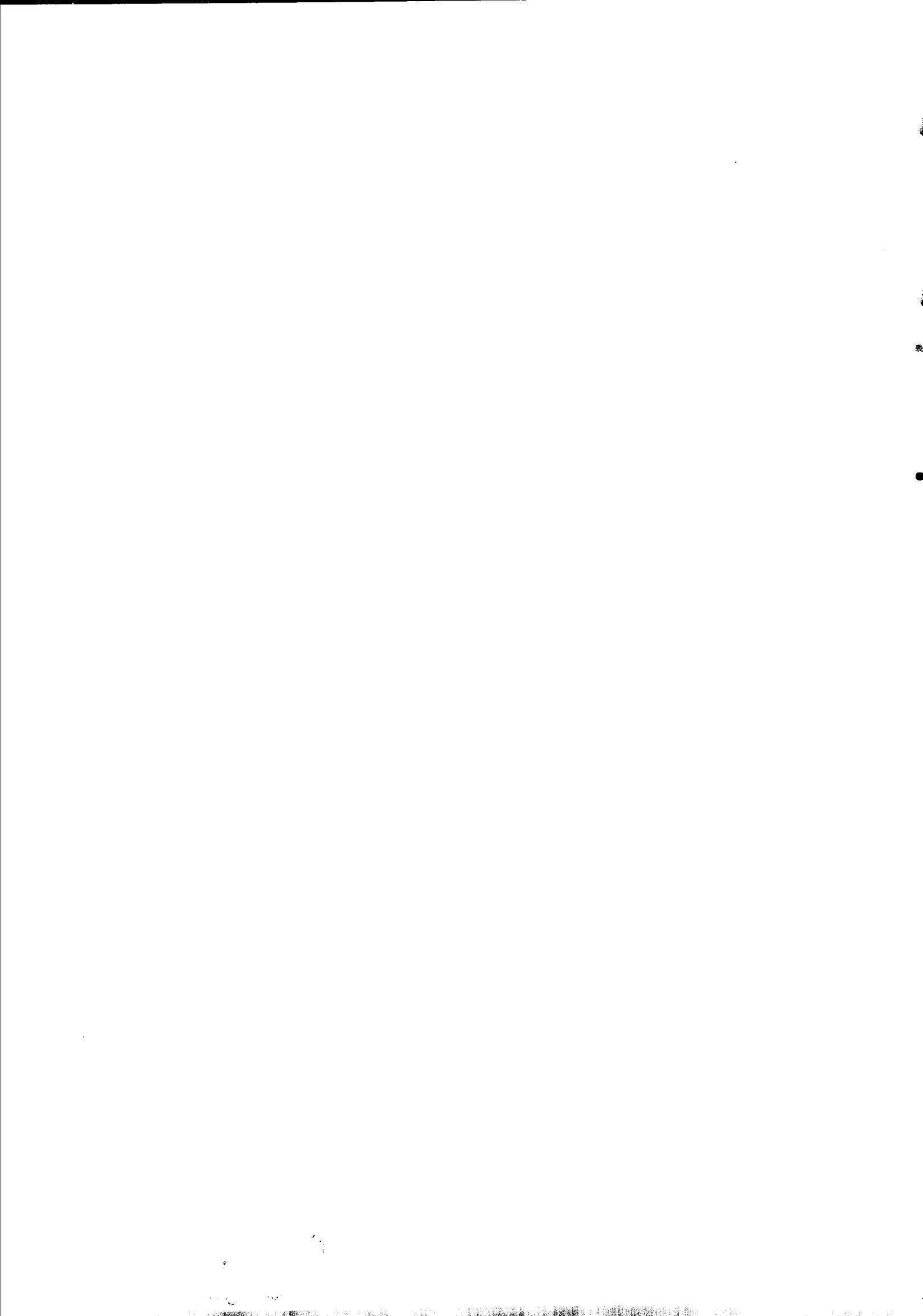
Morphological Analysis and Classification of Types of Surface Corrosion Damage by Digital Image Processing

Ki-Young Choi 599

The Enhancement of the Complex Dielectric Constant of Zinc Oxide Whisker and Analysis of the Microwave Absorption Mechanism

L. S. Chu, M. W. Tang, Z. W. Zhou 604

Invited Papers



Low Temperature Plasma Nitriding and Carburising of Austenitic Stainless Steel for Combined Wear, Corrosion and Fatigue Properties

T Bell, X Li, H Dong

Department of Metallurgy and Materials, School of Engineering,
The university of Birmingham, Birmingham B15 2TT, UK
E-mail: x.li.1@bham.ac.uk

Abstract

Austenitic stainless steels are attractive materials for various industrial sectors to combat environmental and corrosive attack. However, the inherent poor tribological behaviour (in terms of high friction and low wear resistance) has been the main barrier to their wider applications under corrosion-wear conditions. Therefore, it has long been a dream for surface engineering researchers to develop novel surface engineering technologies to effectively enhance the wear resistance of stainless steel surfaces without loss of their attractive "stainless" characteristics. This has been highlighted by the discovery of low temperature plasma nitriding phenomenon in the mid 1980's, where a new phase with a high hardness and good corrosion resistance could be produced on austenitic stainless steel surfaces. Since then great research and development have been made towards combined improvements in wear, corrosion and fatigue properties. This has been demonstrated by various low temperature surface alloying processes (including plasma, ion beam, gaseous and salt bath methods) and increasing numbers of academic publications, reflecting rapidly expanding niche markets in the food, chemical, nuclear and medical sectors.

In this paper, the historical evolution and development of low temperature thermochemical surface alloying processes are overviewed; the research and development of low temperature surface alloying of austenitic stainless steels towards combined improvements in wear, corrosion and fatigue properties are assessed; finally new directions and key areas for future development are identified and discussed.

Keywords: austenitic stainless steel, carburise, corrosion and fatigue properties

Introduction

Austenitic stainless steels are attractive materials for various industrial sectors to combat environmental and corrosive attack. However, the inherent poor tribological behaviour (in terms of high friction and low wear resistance) has been the main barrier to their wider applications under corrosion-wear conditions. As early as 1971 the poor wear resistance of austenitic stainless steels was recognised and investigated by Jean-Paul Lebrun for his PhD at the University of Nancy^[1]. Various attempts have been made in the past decades to modify the surfaces of stainless steels so as to improve their surface hardness and tribological properties. Thermochemical surface engineering, such as nitriding and nitrocarburising, have proved to significantly increase the surface hardness and wear resistance of austenitic stainless steels. However, conventional thermochemical surface treatment ($T > 550^{\circ}\text{C}$) is generally characterised by the precipitation of chromium nitrides, which leads to the depletion of chromium in the austenitic solid solution and thus the material loses its "stainless" features^[2, 3]. Therefore, it has thus become imperative to develop novel technologies that can effectively improve the wear resistance of stainless steel surfaces without adversely effecting the corrosion resistance.

Great research and development efforts have been made during the past 15 years in this direction. These have been highlighted by the discovery of a low temperature nitriding phenomenon in the mid 1980s and plasma carburising recently, where a new phase with a high hardness and good corrosion resistance could be produced on austenitic stainless steel surfaces^[4, 5, 6, 7]. Significant progress has been made by a number of researchers all over the world by using various techniques,

including plasma, ion beam, gaseous, and salt bath methods. On this topic, an International Current Status Seminar was successfully held in 2001 in Japan, and as the fruit of the seminar, a newly published book reflects the enormous strides which have been made in the last few years in the development of low temperature thermochemical processing of austenitic stainless steels^[8].

The present paper discusses various aspects of these two novel plasma processes for austenitic stainless steels, in terms of processing characteristics, structural characterisation, mechanical and chemical property evaluation. The industrial applications of this class of surface engineering technology in diverse sectors are also discussed.

The material used for the investigation was AISI 316 austenitic stainless steel. The chemical composition of the material is 0.06 wt% C, 19.23 wt% Cr, 11.26 wt% Ni, 2.67 wt% Mo, 1.86 wt% Mn, balance Fe. Cylindrical discs, 6–8 mm in thickness, were cut from hot rolled bars of 25mm diameter. The specimens were then manually ground using SiC grinding papers down to 1 200 grade to achieve a fine finish. Plasma carburising was carried out using a 60 kW Klöchner DC plasma treatment unit at about 570 V with a current density of about 30A/m². Various treatment parameters were practised in order to optimise the innovative process. After completing the process, the samples were cooled in the carburising atmosphere until the temperature was below 60°C.

The chemical composition of samples were analysed using a LECO GDS-750 QDP glow discharge spectroscopy (GDS). The optical metallographic microstructures of plasma nitrided specimens were revealed using a 25% HNO₃, 50% HCl and 25% HO₂ etchant. X-ray diffraction (XRD) was carried out on all plasma treated samples for phase identification using a Phillips

X-ray X'Pert diffractometer with Cu-K α radiation. Microstructure and chemical composition were examined using a JEOL 4000FX TEM. The hardness and depth of the modified layer were measured in the sectioned samples using a Leitz microhardness tester. The electrochemical behaviour of the carburised specimens was investigated employing a DC anodic potentiodynamic polarisation technique. The electrolyte used in the test was a 3.5%NaCl solution in deionised water.

Low Temperature Plasma Nitriding

Low temperature plasma nitriding was first investigated by Zhang and Bell ^[9] in the mid of 1980s and independently studied by Ichii et al ^[5] in the same period. They discovered that when plasma nitriding of AISI 304 or 316 stainless steels at temperatures around 400°C, a nitrided layer up to 20 μ m thick could be produced on the sample surface, which had not only a high hardness, but also good corrosion resistance. Since then, great efforts have been made to further investigate the low temperature nitriding phenomenon of austenitic stainless steels, aiming at a better understanding of the nitrided structures and the optimisation of the process for high quality layer production ^[10-12].

Plasma Nitriding Process

Basically, the low temperature plasma nitriding is carried out in a similar way as the conventional nitriding except that the processing temperature is lower and the time sufficiently short. However, there are considerable differences with regard to the microstructures and thus the properties of a low temperature and a high temperature nitrided layers.

Fig. 1 compares the microstructures of plasma nitrided AISI 316 steel produced at 400°C, 550°C for 20 hours in a 500 Pa gas

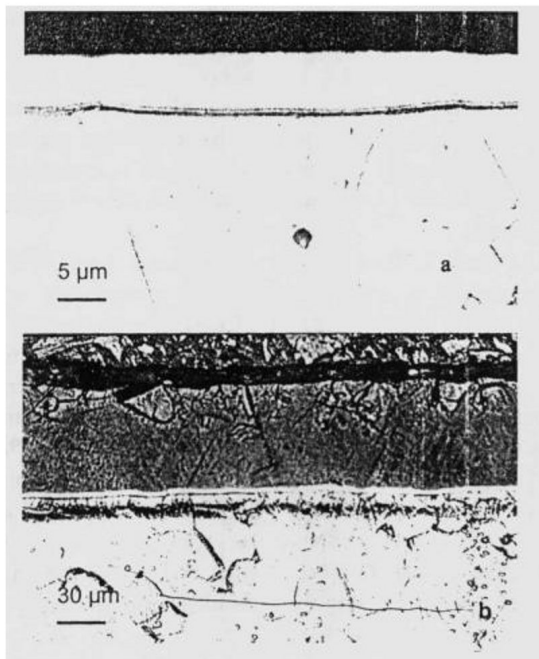


Fig. 1 Optical micrographs showing nitrided layers produced on AISI 316 steel at (a) 400°C and (b) 550°C for 20 hours

mixture of 25%N₂+75%H₂. It can be seen that the low temperature nitrided layer (400°C) is resistant to the etching reagent, such that it appears "bright" under an optical microscope,

Fig. 1a. On the other hand, the higher temperature nitrided layer (550°C) is heavily attacked and appears "dark", Fig. 1b. Comprehensive investigations with regard to the nature, morphology and properties of the nitrided layers, have shown that the "bright" layer produced at lower temperature is precipitation free; whilst the "dark" phases are associated with the precipitation of chromium nitrides. It has been established that once the precipitation of chromium nitrides occurred and the "dark" phase appeared, the corrosion resistance of the steel would become deteriorated.

It is thus important in nitriding practice to select optimised nitriding conditions to avoid the formation of the "dark" phases, thus maintaining corrosion resistance, and at the same time, to produce a relatively thick nitrided layer, thus ensuring the improvement of the tribological properties. Experimental results have shown that the transition from precipitation-free to precipitation occurrence relies very much on the processing temperature. For a specific processing temperature, there exists a critical time. Fig. 2 shows the experimentally established threshold T — t curves for AISI 316 austenitic stainless steel. When the processing temperature and time are so selected that they lie just below the curve, a precipitation-free layer with the highest thickness will be produced ^[6, 13]. The threshold T — t curve therefore has practical importance in the process control of nitriding austenitic stainless steel to achieve combined wear and corrosion resistance.

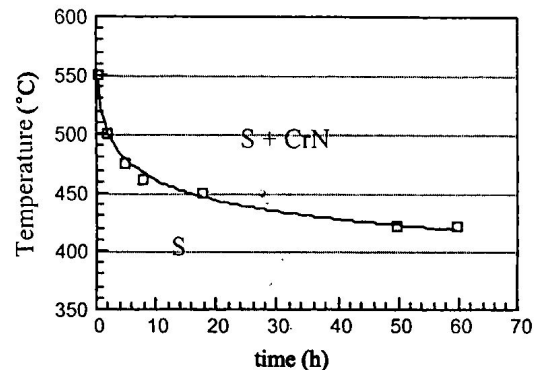


Fig. 2 Threshold Temperature (T) — time (t) curves for the three austenitic stainless steels

Structure of Low Temperature Plasma Nitrided Layer

A variety of analytical techniques have been employed to characterise the structures of the low temperature nitrided layer. It is now generally accepted that the "bright" layer produced at low temperature, as shown in Fig. 1 a, is a single phase which is free from nitride precipitation. However, the nature of this single phase layer has been subject to controversy ever since it was first discovered.

Initially, the 'bright' layer was regarded as a γ -Fe₄N compound layer, since some of its X-ray diffraction peaks appeared at reflection angles close to those from γ nitride ^[15]. Later, Ichii et al ^[14] carried out XRD analysis on a series of low temperature plasma nitrided layers. They concluded that the crystal structure of the nitrided layers could not be identified by the X-ray diffraction peaks according to the ASTM X-ray Diffraction Index, and gave the name of S-phase to this unidentified structure. The term "S phase" is now frequently

used to refer to the low temperature nitrided, and recently the low temperature carburised layer formed on the austenitic stainless steel surface.

Fig. 3 shows the typical X-ray diffraction patterns of low temperature plasma nitrided and untreated austenitic stainless steel AISI 316. Two well-defined peaks of the nitrided layer, indicated as S1 and S2, appear at lower angles than the substrate face-centred cubic austenite (111) and (200) peaks, suggesting that the single phase (S-phase) has a larger lattice parameter than the substrate austenite. The S phase was thus referred to as an expanded austenite, and the expansion has been caused by the supersaturation of nitrogen in austenite^[15, 16]. The S phase was also thought to be a metastable and nitrogen supersaturated solid solution with a disordered face centred cubic (fcc) structure. This was based on the fact that the positions of the X-ray diffraction peaks of S phase deviate from the ideal positions for a face centred cubic lattice^[17]. Some investigators also suggested that the low temperature nitrided layer was corresponding to a body-centred tetragonal (bct) structure^[18].

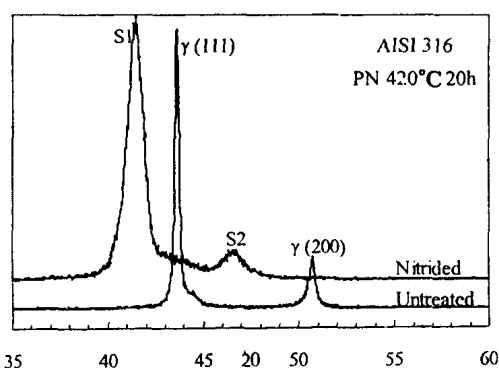


Fig. 3 XRD patterns of untreated and nitrided AISI 316 steel, showing the two broad peaks, S1 and S2, generated from low temperature nitrided layer

A more detailed study has been conducted recently to characterise the low temperature nitrided layers by XRD and TEM analysis^[13, 19]. Several observations have been made regarding the nature of the S phase. Firstly, the S phase indeed has a face centred structure like the original austenite, but its lattice is distorted to such an extent that it no longer exhibits a cubic, but rather a tetragonal structure. The S phase therefore has a face centred tetragonal (fct) crystal structure, which is metastable^[20, 21]. Secondly, a very high compressive residual stress is built up in the nitrided layer, which accounts in part for the observed lattice distortion of the S phase^[13]. Thirdly, the metastable nature of the S phase determines that the nitriding and the service temperatures must be sufficiently low to ensure S-phase formation and to avoid its decomposition to the more stable and equilibrium phase, i.e. austenite and nitrides^[20]. Fourthly, the lattice parameter of the S phase lies between 0.365 nm and 0.390 nm, which is up to 8% larger than that of austenite and the cell rise varies with nitrogen content^[19]. These structural characteristics of S-phase determine that the low temperature nitrided stainless steels have some superior properties which cannot be compared to either by untreated or conventionally higher temperature nitrided steels, as discussed below.

Properties of Low Temperature Plasma Nitrided Layers

The formation of nitrogen S-phase produced a significant

hardening effect on the austenitic stainless steel surface. Typically, the micro-hardness on the treated surface can be as higher than 1000 HV, while it is no more than 250 HV on the untreated surface. As a result, the wear resistance of the stainless steel can be significantly improved by the low temperature plasma nitriding process. Fig. 4 shows that, under dry sliding conditions, the wear volume of the nitrided specimens is more than two orders of magnitude less than that of the untreated specimen. Regardless of the difference in treatment temperature and thus in layer thickness, low temperature nitriding provides improved wear resistance which is comparable to or even higher than the higher temperature nitriding^[22].

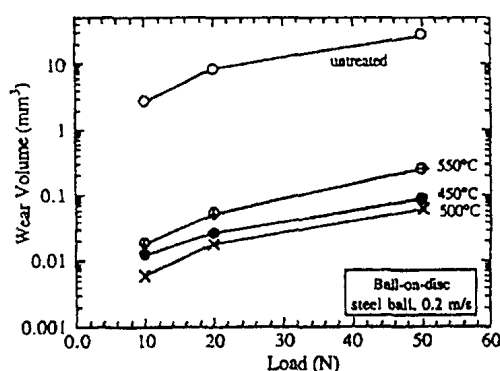


Fig. 4 Wear volume as a function of applied load for AISI 316 specimens sliding against a steel slider for a distance of 1 200 m

More importantly, the low temperature nitrided layer has a corrosion resistance as good as or better than the austenitic stainless steel substrate^[4, 6, 10, 11]. As already shown, the low temperature alloyed layer is resistant to etching by the reagent normally used to reveal the microstructural features of austenitic stainless steel, so that it appears "bright" under a microscope, Fig. 1 a. Electro-chemical corrosion tests in NaCl solutions indicated that low temperature nitriding produced a layer that did not suffer from pitting corrosion even at a very high potential; whilst the untreated steel suffered from pitting corrosion as indicated by a sudden increase in corrosion current density at potentials above a critical value. In contrast, nitriding at higher temperature (above 500°C) resulted in a significant increase in corrosion current density, suggesting a deteriorated corrosion property in the testing solutions^[3, 10, 23]. The cross-section micrographs after electro-chemical test are given in Fig.5. It can be seen that some deep pits were evident for the untreated sample. No pits were presented in the surface layer of the 450°C plasma nitrided sample. However, large and deep pits were present in the 550°C nitrided sample, which penetrated throughout the whole nitrided layer and were stopped at the case/substrate interface.

Due to the combined enhancement in hardness and corrosion resistance, the low temperature nitrided layer exhibits much improved wear resistance not only under dry and other non-corrosive environments, but also under severe corrosive environments. Fig. 6 compares the wear curves for various AISI 316 specimens by pin-on-disc tests in a corrosive solution of 10% HCl + 5% HNO₃ + 85% H₂O. It can be seen that in the tested solution, the specimens nitrided at 500°C and 550°C did not improve the corrosive wear resistance. Low temperature nitriding, on the other hand, significantly improved the corrosive wear resistance of the steel. Surface and subsurface

examination of the worn specimens revealed that material lost from the high temperature nitrided specimens was mainly due to corrosion, whilst that from the untreated specimen was due to metallic wear^[24].

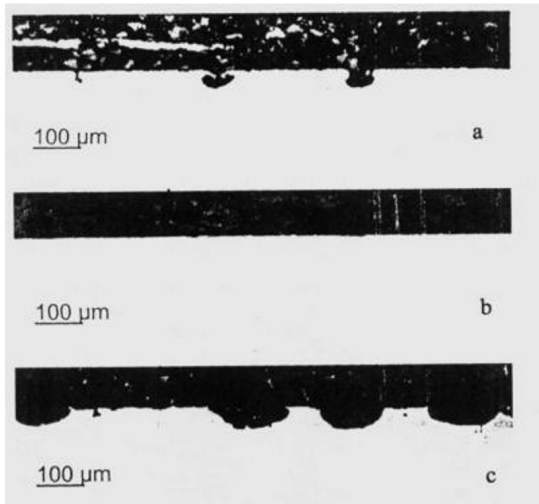


Fig. 5 Cross-section view of (a) untreated, (b) 450°C/20h nitrided and (c) 550°C/20h nitrided surface after electro-chemical tests.

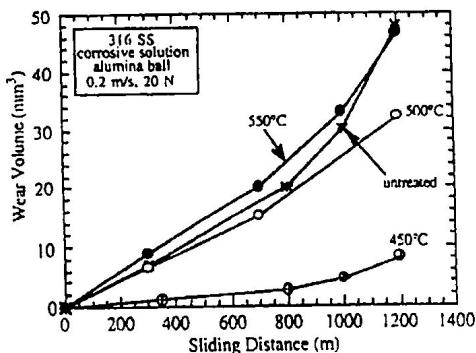


Fig. 6 Wear curves generated during pin-on-disc sliding testing in a 10% HCl + 5% HNO₃ + 85% H₂O solution

Apart from the improvement in wear and corrosion resistance, the fatigue properties of the austenitic stainless steels can be substantially improved after low temperature nitriding. This is mainly due to the formation of a hardened layer which delays the fatigue crack initiation, and the introduction of compressive residual stress which reduces the fatigue crack propagation rate^[25, 26]. As an example, Fig. 7 shows the plain fatigue and fretting fatigue S-N curves of AISI 316 steel before and after plasma nitriding at 400°C for 15 hours. Fatigue tests were carried out under rotating bending conditions, and fretting was achieved by a specially designed assembly which allows two contact pads (316 steel) to be clamped symmetrically on the sample surface during fatigue tests. It can be seen that plasma nitriding at a temperature as low as 400°C improves the plain fatigue strength (at 10⁷ cycles) of the steel by 25%, but its effect on fretting fatigue is even more significant. At the high cycle fatigue (HCF) region, the fretting fatigue strength of the nitrided steel is 2 to 3 times greater than that for the untreated material. Whilst at low cycle fatigue (LCF), there is little to distinguish between the fretting fatigue curve of the nitrided samples and that of the as-received samples under plain fatigue conditions, indicating the deleterious effect of fretting at LCF region has been eliminated by the low temperature plasma nitriding

employed. These results regarding the effectiveness of low temperature plasma nitriding in improving both plain fatigue and fretting behaviour of austenitic stainless steel have important implications for industrial applications where fatigue loading and/or fretting are involved.

Low Temperature Plasma Carburising

The low temperature plasma nitrided austenitic stainless steels perform satisfactorily in many industrial applications. However, there are several technical problems associated with the plasma nitriding technique, a major one being a very thin as-nitrided S-phase layer^[27]. Great efforts have been made in the past with the aim to increase the layer thickness. However, due to the metastable nature of the nitrogen S phase and the constraints imposed on processing temperature and time, it is rather difficult to produce a precipitation-free layer thicker than 20 μm. The thin, hard nitrided layer with an abrupt interface is expected to have a relatively low load bearing capacity and limited resistance to impact.

Recently, it has been found that some of the problems with nitriding can be eliminated if carbon, rather than nitrogen, is used as a major alloying species during the plasma surface engineering process^[17]. This has led to the development of a low temperature plasma carburising process, which is carried out at temperatures between 300°C and 550°C to facilitate the diffusion of carbon into the stainless steel surface, forming a carbon S-phase layer^[28]. The process characteristics, the structure of the carbon S-phase layer, and the properties of the plasma carburised austenitic stainless steel are discussed below.

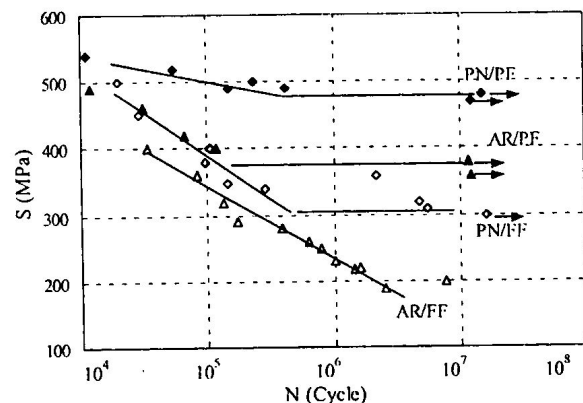


Fig. 7 Plain fatigue (PF) and fretting fatigue (FF) S-N curves of as-received (AR) and plasma nitrided (PN) 316 steel. PN at 400°C for 15 hours

Low Temperature Carburising Process

The processing cycle in low temperature plasma carburising is similar to that in plasma nitriding, but a carbon bearing gas such as a mixture of methane and hydrogen, is used in carburising. Under the glow discharge of a plasma, activated carbon species are generated and then transferred to the austenitic stainless steel surface and diffused into the material, forming a carbon-enriched layer. When the processing temperature is high, chromium carbides will form in the carburised layer, as in the situation with conventional carburising of high alloy steels^[29], and the corrosion characteristics of stainless steels will be damaged. However, when the processing temperature is sufficiently low, carbide