

LECH PAWLOWSKI

THE SCIENCE AND ENGINEERING OF  
**THERMAL SPRAY  
COATINGS**



SECOND EDITION

 WILEY

# Contents

<i>Preface to the Second Edition</i>	xv
<i>Preface to the First Edition</i>	xvii
<i>Acronyms, Abbreviations and Symbols</i>	xxi
<b>1 Materials Used for Spraying</b>	<b>1</b>
1.1 Methods of Powders Production	3
1.1.1 Atomization	5
1.1.2 Sintering or Fusion	8
1.1.3 Spray Drying (Agglomeration)	11
1.1.4 Cladding	20
1.1.5 Mechanical Alloying (Mechanofusion)	26
1.1.6 Self-propagating High-temperature Synthesis (SHS)	28
1.1.7 Other Methods	32
1.2 Methods of Powders Characterization	35
1.2.1 Grain Size	35
1.2.2 Chemical and Phase Composition	38
1.2.3 Internal and External Morphology	39
1.2.4 High-temperature Behaviour	41
1.2.5 Apparent Density and Flowability	42
1.3 Feeding, Transport and Injection of Powders	42
1.3.1 Powder Feeders	43
1.3.2 Transport of Powders	44
1.3.3 Injection of Powders	44
References	47

<b>2</b>	<b>Pre-Spray Treatment</b>	<b>53</b>
2.1	Introduction	53
2.2	Surface Cleaning	54
2.3	Substrate Shaping	55
2.4	Surface Activation	56
2.5	Masking	64
	References	66
<b>3</b>	<b>Thermal Spraying Techniques</b>	<b>67</b>
3.1	Introduction	67
3.2	Flame Spraying (FS)	69
3.2.1	History	69
3.2.2	Principles	70
3.2.3	Process Parameters	71
3.2.4	Coating Properties	74
3.3	Atmospheric Plasma Spraying (APS)	74
3.3.1	History	74
3.3.2	Principles	74
3.3.3	Process Parameters	75
3.3.4	Coating Properties	79
3.4	Arc Spraying (AS)	79
3.4.1	Principles	79
3.4.2	Process Parameters	80
3.4.3	Coating Properties	81
3.5	Detonation-Gun Spraying (D-GUN)	82
3.5.1	History	82
3.5.2	Principles	82
3.5.3	Process Parameters	83
3.5.4	Coating Properties	84
3.6	High-Velocity Oxy-Fuel (HVOF) Spraying	85
3.6.1	History	85
3.6.2	Principles	85
3.6.3	Process Parameters	86
3.6.4	Coating Properties	89
3.7	Vacuum Plasma Spraying (VPS)	89
3.7.1	History	89
3.7.2	Principles	89
3.7.3	Process Parameters	91
3.7.4	Coating Properties	92
3.8	Controlled-Atmosphere Plasma Spraying (CAPS)	93
3.8.1	History	93
3.8.2	Principles	93

3.8.3	Process Parameters	94
3.8.4	Coating Properties	96
3.9	Cold-Gas Spraying Method (CGSM)	96
3.9.1	History	96
3.9.2	Principles	97
3.9.3	Process Parameters	97
3.9.4	Coating Properties	100
3.10	New Developments in Thermal Spray Techniques	100
	References	107
<b>4</b>	<b>Post-Spray Treatment</b>	<b>115</b>
4.1	Heat Treatment	115
4.1.1	Electromagnetic Treatment	116
4.1.2	Furnace Treatment	149
4.1.3	Hot Isostatic Pressing (HIP)	150
4.1.4	Combustion Flame Re-melting	152
4.2	Impregnation	154
4.2.1	Inorganic Sealants	154
4.2.2	Organic Sealants	157
4.3	Finishing	158
4.3.1	Grinding	158
4.3.2	Polishing and Lapping	159
	References	159
<b>5</b>	<b>Physics and Chemistry of Thermal Spraying</b>	<b>167</b>
5.1	Jets and Flames	168
5.1.1	Properties of Jets and Flames	169
5.2	Momentum Transfer between Jets or Flames and Sprayed Particles	180
5.2.1	Theoretical Description	181
5.2.2	Experimental Determination of Sprayed Particles' Velocities	186
5.2.3	Examples of Experimental Determination of Particles Velocities	190
5.3	Heat Transfer between Jets or Flames and Sprayed Particles	192
5.3.1	Theoretical Description	193
5.3.2	Methods of Particles' Temperature Measurements	208
5.4	Chemical Modification at Flight of Sprayed Particles	210
	References	214

<b>6</b>	<b>Coating Build-Up</b>	<b>221</b>
6.1	Impact of Particles	222
6.1.1	Particle Deformation	223
6.1.2	Particle Temperature at Impact	236
6.1.3	Nucleation, Solidification and Crystal Growth	241
6.1.4	Mechanisms of Adhesion	246
6.2	Coating Growth	249
6.2.1	Mechanism of Coating Growth	249
6.2.2	Temperature of Coatings at Spraying	251
6.2.3	Generation of Thermal Stresses at Spraying	255
6.2.4	Coatings Surfaces	264
6.3	Microstructure of the Coatings	264
6.3.1	Crystal Phase Composition	264
6.3.2	Coatings' Inhomogeneity	278
6.3.3	Final Microstructure of Sprayed Coatings	280
6.4	Thermally Sprayed Composites	281
6.4.1	Classification of Sprayed Composites	282
6.4.2	Composite Coating Manufacturing	282
	References	284
<b>7</b>	<b>Methods of Coatings' Characterization</b>	<b>291</b>
7.1	Methods of Microstructure Characterization	292
7.1.1	Methods of Chemical Analysis	297
7.1.2	Crystallographic Analyses	303
7.1.3	Microstructure Analyses	307
7.1.4	Other Applied Methods	315
7.2	Mechanical Properties of Coatings	317
7.2.1	Adhesion Determination	318
7.2.2	Hardness and Microhardness	324
7.2.3	Elastic Moduli, Strength and Ductility	325
7.2.4	Properties Related to Mechanics of Coating Fracture	332
7.2.5	Friction and Wear	334
7.2.6	Residual Stresses	339
7.3	Physical Properties of Coatings	340
7.3.1	Thickness, Porosity and Density	341
7.3.2	Thermophysical Properties	342
7.3.3	Thermal Shock Resistance	348
7.4	Electrical Properties of Coatings	350
7.4.1	Electrical Conductivity	350

7.4.2	Properties of Dielectrics	353
7.4.3	Electron Emission from Surfaces	357
7.5	Magnetic Properties of Coatings	357
7.6	Chemical Properties of Coatings	359
7.6.1	Aqueous Corrosion	359
7.6.2	Hot gas Corrosion	363
7.7	Characterization of Coatings' Quality	364
7.7.1	Acoustical Methods	365
7.7.2	Thermal Methods	368
	References	370
<b>8</b>	<b>Properties of Coatings</b>	<b>383</b>
8.1	Design of Experiments	384
8.2	Mechanical Properties	389
8.2.1	Hardness and Microhardness	389
8.2.2	Tensile Adhesion Strength	403
8.2.3	Elastic Moduli, Strengths and Fracture Toughness	412
8.2.4	Friction and Wear	434
8.3	Thermophysical Properties	452
8.3.1	Thermal Conductivity and Diffusivity	454
8.3.2	Specific Heat	471
8.3.3	Thermal Expansion	472
8.3.4	Emissivity	479
8.3.5	Thermal Shock Resistance	480
8.4	Electric Properties	484
8.4.1	Properties of Conductors	484
8.4.2	Properties of Resistors	492
8.4.3	Properties of Dielectrics	493
8.4.4	Electric Field Emitters	500
8.4.5	Properties of Superconductors	501
8.5	Magnetic Properties	502
8.5.1	Soft Magnets	502
8.5.2	Hard Magnets	504
8.6	Optical Properties	504
8.6.1	Decorative Coatings	505
8.6.2	Optically Functional Coatings	505
8.7	Corrosion Resistance	507
8.7.1	Aqueous Corrosion	507
8.7.2	Hot-medium Corrosion	518
	References	521

<b>9</b>	<b>Applications of Coatings</b>	<b>543</b>
9.1	Aeronautical and Space Industries	545
9.1.1	Aero-engines	545
9.1.2	Landing-gear Components	549
9.1.3	Rocket Thrust-chamber Liners	550
9.2	Agroalimentary Industry	551
9.3	Automobile Industry	551
9.4	Ceramics Industry	554
9.4.1	Free-standing Samples	554
9.4.2	Brick-Clay Extruders	555
9.4.3	Crucibles to Melt Oxide Ceramics	557
9.4.4	Ceramic Membranes	557
9.5	Chemical Industry	557
9.5.1	Photocatalytic Surfaces	557
9.5.2	Tools in Petrol Search Installations	559
9.5.3	Vessels in Chemical Refineries	560
9.5.4	Gas-well Tubing	560
9.5.5	Polymeric Coatings on Pipeline Components	560
9.5.6	Ozonizer Tubes	561
9.6	Civil Engineering	562
9.7	Decorative Coatings	563
9.8	Electronics Industry	563
9.8.1	Heaters	564
9.8.2	Sources for Sputtering	565
9.8.3	Substrates for Hybrid Microelectronics	565
9.8.4	Capacitor Electrodes	566
9.8.5	Conductor Paths for Hybrid Electronics	566
9.8.6	Microwave Integrated Circuits	566
9.9	Energy Generation and Transport	567
9.9.1	Solid-oxide Fuel Cell (SOFCs)	567
9.9.2	Thermopile Devices for Thermoelectric Generators	569
9.9.3	Boilers in Power-generation Plants	571
9.9.4	Stationary Gas Turbines	571
9.9.5	Hydropower Stations	572
9.9.6	MHD Generators	572
9.10	Iron and Steel Industries	572
9.10.1	Continuous Annealing Line (CAL)	573
9.10.2	Continuous Galvanizing Section	574
9.10.3	Slab Cooling Pipes	574
9.11	Machine Building Industry	574

9.12	Medicine	575
9.13	Mining Industry	577
9.14	Non-ferrous Metal Industry	577
	9.14.1 Hot extrusion Dies	577
	9.14.2 Protective Coatings against Liquid Copper	578
	9.14.3 Protective Coatings against Liquid Zirconium	578
9.15	Nuclear Industry	579
	9.15.1 Components of Tokamak Device	579
	9.15.2 Magnetic-fusion Energy Device	579
9.16	Paper Industry	580
	9.16.1 Dryers	580
	9.16.2 Gloss Calender Rolls	582
	9.16.3 Tubing in Boilers	582
9.17	Printing and Packaging Industries	583
	9.17.1 Corona Rolls	583
	9.17.2 Anilox Rolls	585
9.18	Shipbuilding and Naval Industries	588
	9.18.1 Marine Gas-turbine Engines	588
	9.18.2 Steam Valve Stems	588
	9.18.3 Non-skid Helicopter Flight Deck	588
	References	588