
SINTERING THEORY AND PRACTICE

Randall M. German

The Pennsylvania State University
University Park, Pennsylvania

Fachbereich Materialwissenschaft
der Techn. Hochschule Darmstadt

Inv.-Nr.: 1332



A WILEY-INTERSCIENCE PUBLICATION

JOHN WILEY & SONS, INC.

New York / Chichester / Brisbane / Toronto / Singapore

CONTENTS

Preface	vii
1 Introduction to Sintering	1
Overview / 1	
Brief History of Sintering / 3	
The Sintering Process / 4	
Definitions and Nomenclature / 8	
Overview of Sintering Techniques / 13	
Goals in Sintering Studies / 16	
Problems with Sintering Theory / 19	
Related Topics / 20	
References / 20	
2 Sintering Measurement Techniques	23
Introduction / 23	
Compaction Effects / 24	
Density, Porosity, and Pore Characteristics / 26	
Microstructure / 32	
Shrinkage and Swelling / 39	
Surface Area / 46	
Thermal, Electrical, and Magnetic Responses / 51	
Mechanical Response / 55	
Homogenization and Reactions / 59	
Summary / 61	
References / 63	

3 Solid-State Sintering Fundamentals

67

- Theoretical Introduction / 68
 - Basic Concepts / 68
 - Assumptions of Sintering Theories / 72
 - Coarsening and Densification / 73
- Sintering Stress / 75
- Mass Transport Mechanisms / 78
 - Viscous Flow / 80
 - Evaporation–Condensation / 82
 - Surface Diffusion / 86
 - Volume Diffusion / 88
 - Grain Boundary Diffusion / 91
 - Plastic Flow / 93
 - Overview of Mass Transport Processes / 94
- Stages of Sintering / 95
 - Adhesion, Rearrangement, and Repacking / 96
 - Initial-Stage Neck Growth / 98
 - Intermediate Stage / 103
 - Final Stage / 110
 - Coarsening Versus Densification / 115
- Data Analysis / 121
- Calculations of Sintering Rates / 126
- Sintering Diagrams / 132
- Summary / 136
- References / 137

4 Microstructure and Processing Relations in Solid-State Sintering

142

- Introduction / 142
- Powder Characteristics / 143
- Particle Packing / 147
- Pore Structure / 155
- Grain Structure / 161
- Microstructure Evolution Dynamics / 166
- Heating Rate / 170

Solid-State Sintering Cycles /	171
References /	174

5 Solid-State Sintering of Mixed Powders 178

Categorization of Physical and Chemical Interactions /	178
Packing and Sintering Behavior of Mixed Particles /	181
Loose Packing Rules /	181
Sintering Shrinkage Rules /	184
Sintering Stress Concepts /	188
Sintering Density Predictions /	191
Sintering Composites with an Inert Phase /	192
Homogenization Kinetics /	197
Swelling and Pore Generation in Chemically Active Systems /	201
Enhanced Sintering /	207
Activated Sintering /	209
Microstructure Control /	214
Co-fire Systems /	218
Summary /	219
References /	221

6 Liquid-Phase Sintering 225

Overview of Sintering in the Presence of a Liquid Phase /	226
Key Thermodynamics and Kinetic Factors /	231
Phase Diagram Concepts /	231
Interfacial Energies /	232
Wetting, Spreading, Penetration, and Segregation /	235
Contact Angle /	237
Solubility /	239
Capillarity /	240
Contact Force /	243
Viscous Flow of Solid-Liquid Systems /	244
Contact Formation /	247
Microstructure Characteristics /	247
Volume Fraction /	247
Dihedral Angle /	248

Intergranular Bonds / 252	
Coordination and Connectivity / 254	
Contiguity / 256	
Grain Shape / 258	
Heating and Melting Stage / 261	
Solubility Role in Densification / 263	
Melt Formation / 269	
Particle Fragmentation / 270	
Rearrangement / 271	
Solution–Reprecipitation Stage / 274	
Grain Shape Accommodation / 275	
Densification / 276	
Intergranular Neck Growth / 280	
Coalescence / 282	
Pore Filling / 284	
Microstructural Coarsening / 286	
Final-Stage Densification / 288	
Grain Growth / 293	
Grain Size Distribution / 299	
Discontinuous Grain Growth / 300	
Inhibited Grain Growth / 301	
Other Microstructural Changes / 302	
Summary / 304	
References / 307	

7 Pressure-Assisted Sintering

313

Introduction / 314	
Applications / 315	
Enhanced Densification / 316	
Stress Amplification at Pores / 318	
Constraints on Pressure-Assisted Densification / 322	
Stress–Strain States in Pressure-Assisted Sintering / 326	
Deformation Mechanisms / 330	
Plastic Flow / 330	
Viscous Flow / 332	
Creep Flow / 333	

Densification Maps /	338
Pressure-Assisted Sintering Processes /	340
Pressure-Enhanced Sintering /	341
Forging /	343
Powder Extrusion /	347
Shock Wave Consolidation /	348
Uniaxial Hot Pressing /	350
Hot Isostatic Pressing /	353
Triaxial Pressurization /	359
Reactive Processes /	361
Novel Pressure-Assisted Sintering Techniques /	362
Problems with Pressure-Assisted Sintering /	362
Summary /	366
References /	368

8 Novel Sintering Techniques

373

Introduction /	373
Supersolidus Liquid-Phase Sintering /	374
Densification Mechanism /	375
Processing Parameters /	379
Densification Model /	380
Practice /	383
Infiltration Sintering /	385
Activated Liquid-Phase Sintering /	389
Transient Liquid /	391
Reactive Processes /	395
Reactive Sintering /	397
Reaction Bonding /	400
Reactive Hot Compaction /	402
Novel Heating Techniques /	403
Induction Heating /	404
Microwave Heating /	408
Plasma Heating /	411
Electric Discharge Heating /	412
Laser Heating /	414

Summary / 414

References / 416

9 Sintering Atmospheres

421

Introduction / 421

Atmosphere Types / 423

Gases / 423

Vacuum / 426

Thermodynamics / 427

Oxidation–Reduction / 428

Carburization–Decarburization / 431

Other Examples / 435

Impurity Effects / 438

Summary / 444

References / 447

10 Sintering Practice

450

Introduction / 451

Product Control in Sintering / 451

Dimensions / 452

Defect Growth / 461

Microstructure and Properties / 463

Green Microstructure Effects / 465

Processing Limits / 466

Equipment Concerns / 472

Furnace Type / 472

Heat Sources / 474

Supports / 476

Process Measurement / 478

Heat Transport / 480

Heating and Cooling Rates / 482

Example Sintering Cycles / 483

Alumina / 483

Aluminum / 484

Brass and Bronze / 485

Cemented Carbides / 486	
Copper and Copper Alloys / 486	
Silicon Carbide / 487	
Silicon Nitride / 487	
Stainless Steel / 489	
Steels / 491	
Tool Steels / 493	
Tungsten Heavy Alloys / 494	
Zirconia / 495	
Summary of Practical Constraints / 495	
References / 496	
11 Future Directions	507
Introduction / 507	
Green Microstructure / 508	
Heating Pathway / 509	
Microstructure Coarsening / 510	
Cracks and Other Defects / 512	
Liquid-Phase Sintering / 513	
Pressure-Assisted Sintering / 514	
Impurity and Atmosphere Effects / 514	
Small Particles / 516	
Advanced Materials / 516	
Improved Models / 517	
Novel Processing Techniques / 518	
References / 519	
Appendix: Data Relevant to Sintering Studies	524
Sources of Materials Constants and Properties / 535	
Index	537