



Table of contents

Preface	i
Table of contents.....	iii
<i>i</i> abstract.....	vii
<i>ii</i> abstract (German)	viii
<i>iii</i> Nomenclature.....	ix
<i>iv</i> List of figures	xiii
<i>v</i> List of tables	xvi
1 Introduction	1
2 Composite materials and their properties	10
2.1 Building blocks of composites: Properties of ceramics, polymers, and metals	10
2.1.1 Properties of ceramics	10
2.1.2 Properties of polymers	12
2.1.3 Properties of metals and metal alloys	15
2.2 Existing types of composites	15
2.2.1 Composite materials in nature.....	15
2.2.2 Bio-inspired artificial composites.....	17
2.2.3 Fiber-reinforced polymer-matrix composites	20
2.2.4 Particulate-reinforced polymer-matrix composites.....	21
2.2.5 Other types of composites.....	23
2.3 Properties of ceramic-polymer composite materials	23
2.3.1 Mechanical properties.....	24
2.3.2 Mechanical failure.....	27
2.3.3 Possible applications of highly-filled ceramic-polymer composites.....	30
2.4 State of the art for fabricating ceramic-polymer composites	31
3 Fluidization and spouted bed granulation technology	34
3.1 Fundamentals on fluidization and spouting	34
3.1.1 Fluidized and spouted beds	36
3.1.2 Pressure drop and minimum fluidization velocity.....	37
3.1.3 Fluidization of fine particles	38
3.2 Agglomeration mechanisms	41
3.2.1 Effect of agglomeration on particle properties.....	42
3.2.2 Contact forces.....	43
3.3 The spouted bed spray granulation process.....	44
3.3.1 Properties of the spraying liquid	46



3.3.2	Preparation of spraying liquid suspensions via comminution	48
3.3.3	Modeling of the spray granulation process.....	50
4	Experimental setup.....	51
4.1	Materials	51
4.2	Spouted bed apparatus.....	52
4.2.1	Specifications of the spouted bed apparatus	54
4.2.2	Preparation of the spraying liquid.....	55
4.3	Granule characterization.....	56
4.3.1	Optical particle measurement	56
4.3.2	Static light scattering.....	56
4.3.3	Scanning electron microscopy.....	57
4.3.4	Thermogravimetric analysis	57
4.3.5	Muffle furnace.....	58
4.4	Warm-pressing and sample preparation.....	58
4.4.1	Four-stamp press.....	58
4.4.2	Sample preparation.....	60
4.5	Composite materials characterization.....	60
4.5.1	DESY-Beamline	60
4.5.2	Vickers hardness.....	60
4.5.3	Four-point bending.....	61
4.5.4	Fracture toughness.....	63
4.5.5	Tensile strength.....	64
5	Formulation of ceramic-polymer composites with the spouted bed technology	66
5.1	Preparation of the spraying liquid	67
5.1.1	Selection of polymer	67
5.1.2	Preparation of polymer solutions.....	70
5.1.3	Preparation of poly(amide imide) suspensions	71
5.1.4	Other possibilities to prepare the spraying liquid.....	76
5.2	Dimensioning the granulation process	77
5.3	Fabrication of ceramic-polymer granules.....	84
5.3.1	Granulation of two different particles sizes and a polymer	85
5.3.2	Granulation with polymer suspensions.....	86
5.3.3	Granulation with low-vapor-pressure solvents.....	87
5.3.4	Granulation of alumina platelets of various sizes.....	88
5.4	Warm-pressing of the granules to the composite	89
5.4.1	Warm pressing of PVB-coated granules	89
5.4.2	Warm pressing of granules coated with high-performance polymers	89



5.4.3	Warm-pressing of NEAT poly(ether sulfone)	90
5.4.4	Influence of polymer type on the sample unloading.....	90
5.5	Waste management and sustainability of the material.....	91
6	Analysis and mechanical testing of the fabricated composites.....	92
6.1	Compositional analysis.....	92
6.1.1	Filling degree and porosity of the fabricated samples.....	92
6.2	Morphological analysis.....	94
6.2.1	Fracture surfaces.....	94
6.2.2	X-ray computed tomographic analysis.....	95
6.3	Mechanical analysis.....	97
6.3.1	Preparation of test specimens from the pressed samples.....	97
6.3.2	Mechanical properties of alumina-PVB composites	98
6.3.3	Mechanical properties of composites with high-performance polymers	104
7	Discrete Element Modeling of ceramic-polymer composites.....	107
7.1	Fundamentals of the Discrete Element Method.....	108
7.1.1	Types of forces	109
7.1.2	Particle shapes in DEM.....	110
7.2	Review of mechanical testing of particulate matter with DEM.....	110
7.3	Bonding models for the soft phase.....	111
7.3.1	Linear-elastic model	111
7.3.2	Nonelastic models	113
7.4	Generation of ceramic-polymer specimens for DEM modeling.....	113
7.4.1	Particle generation with two-radii concept.....	114
7.4.2	Distribution of particles within the specimen.....	117
7.5	Simulation of mechanical tests of ceramic-polymer composites with DEM.....	119
7.5.2	Outlook: Simulation of crack propagation and plasticity	124
8	The route towards hierarchical, multifunctional composites	125
8.1	Granulation of prestructured composites	125
8.2	Consecutive granulation with different polymers	127
8.3	Granulation with fiber-reinforced polymers.....	127
8.4	Addition of metals.....	129
8.5	Fabrication of multifunctional composites	130
9	Summary	133
10	References.....	136
11	Appendix.....	146
A	List of publications	146
1.	Peer-reviewed articles.....	146



Table of contents

2. Conference proceedings.....	146
<i>B</i> Supplementary details.....	147
3. Calculation of Γ_M for the computation of the fracture toughness.....	147
4. Calculation of the terminal velocity.....	147
5. Vickers indentation prefactor.....	148
6. List of sawing parameters	148
7. Compositional analysis of the pressed samples.....	148
8. Attritor-milling of the poly(amide imide suspensions).....	149
9. Zeta potential / Differential Scanning Calorimetry.....	149
<i>C</i> Glossary.....	150
<i>D</i> List of experimental equipment.....	155
Curriculum vitae.....	157