

Contents

1 General Problems of Propagation of Laser Radiation in Gases and Plasma and Physical Processes on the Surface of Condensed Media	1
1.1 Propagation and Focusing of Radiation in Vacuum, Gases and Plasma	2
1.1.1 Focusing of Light in Vacuum	2
1.1.2 Propagation of Laser Radiation in Gases and Plasma	4
1.2 Absorption, Reflection, and Propagation of Radiation in Cavities in Condensed Media	8
1.2.1 Flat Surface	8
1.2.2 Propagation of Laser Radiation in a Narrow Channel in a Metal	12
1.2.3 Waveguide Radiation Propagation Regime	15
1.2.4 Propagation of Plane-Polarized Radiation in a Cylindrical Keyhole	17
1.3 Physical Processes on the Surface of Condensed Media: The Interaction of Vapor with the Surrounding Gas	20
1.3.1 Melting	20
1.3.2 Vaporization	21
1.3.3 Melting–Solidification Dynamics Taking Vaporization into Account	22
1.3.4 Stationary Interaction of a Vapor Jet with the Surrounding Gas	25
1.4 Vaporization Kinetics and Hydrodynamics	27
1.4.1 Condensation	33
1.5 Instability of the Laser-Induced Vaporization of Condensed Media	36
References	43

2	Mechanisms of Laser Processing of Metal Surfaces	45
2.1	Thermal Model of Laser Hardening of the Steel Surface	45
2.1.1	Qualitative Consideration of the Stationary Thermal Model of Metal Hardening.....	46
2.1.2	Comparison with Experiments.....	49
2.1.3	Numerical Calculations	52
2.1.4	Processing of Metal Surfaces by the Oscillating Beam of a CO ₂ Laser.....	54
2.2	Hydrodynamical Models of Laser-Induced Alloying of Metal Surfaces	57
2.2.1	Analysis of Experimental Data	58
2.2.2	Theoretical Consideration of Melt Motion During Alloying of Metals	61
2.2.3	Analytic Consideration of Liquid Metal Motion Caused by Thermocapillary Forces	62
2.2.4	Numerical Modelling of a Melt Flow During Alloying	64
2.2.5	Nonlinear Effects and the Instability of the Melt Surface Shape in the Marangoni Flow	68
2.2.6	Development of the Multi-Vortex Structure of the Melt Flow	74
2.2.7	Influence of Surfactants on Heat-and-Mass Transfer During Laser Alloying	78
2.2.8	Mass-Transfer Kinetics During Gas-Phase Alloying	80
2.2.9	Alloying of a Moving Sample Surface by Stationary Laser Radiation	84
2.2.10	Melt Flow Upon Pulsed and Repetitively Pulses Irradiation	89
2.2.11	Thermocapillary Processes in the Dynamics of Gas Bubbles in a Melt Pool	91
2.3	Physical Mechanisms of Cladding	94
2.4	Mechanisms of Laser-Induced Surface Cleaning.....	108
2.4.1	Cleaning of Surfaces from Microparticles	109
2.4.2	Laser-Induced Solid Surface Cleaning from Films	111
2.4.3	Physical Model of Water Surface Cleaning from Thin Films of Petroleum Products.....	114
2.4.4	Laser-Induced Metal Surface Cleaning from Radionuclides.....	118
2.5	Modelling of Selective Laser Melting.....	122
2.5.1	Structures	122
2.5.2	Heat Conduction of Powders in Vacuum	123
2.5.3	Calculation of Thermal and Optical Constants of Initial Materials.....	126
2.5.4	Volume and Surface Absorption Coefficients	127
2.5.5	Powder Mixtures	130
2.5.6	Thermal Model of Selective Laser Sintering.....	132

2.5.7	Instability of Selective Laser Melting	135
2.5.8	Thermal Hydrodynamic Model of Selective Laser Sintering	136
	References	139
3	Plasma Phenomena in Laser Processing of Materials	145
3.1	Thermal Properties of the Plasma of Noble and Molecular Gases and Metal Vapors.....	145
3.1.1	Plasma Emission	149
3.2	Mechanisms of the cw Laser-Induced Breakdown of Gases Near Solid Surfaces.....	150
3.2.1	Stationary Breakdown of Gases in the Absence of a Target.....	150
3.2.2	Nonequilibrium Mechanism of Optical Breakdown in Gases Near a Target	155
3.2.3	Thermal Model of Optical Breakdown in Gases Near a Target	162
3.2.4	Theoretical Model	163
3.2.5	Numerical Calculation of the Thermal Model	166
3.2.6	Optical Breakdown of Chemically Active Gases Near a Target	168
3.2.7	Optical Breakdown During Laser Welding	169
3.3	The Numerical Model of an Erosion Plume During Welding.....	172
3.4	Optical Discharge Burning Near a Sample Surface	173
3.4.1	Theoretical Models of a Continuous Optical Discharge.....	174
3.4.2	The Heat-Conduction COD Model	177
3.4.3	COD Model Taking into Account the Heat Conduction and Emission of Plasma	179
3.4.4	Numerical Calculations of Optical Discharge Parameters...	182
3.4.5	The Radiative-Conductive COD Model	186
3.5	LCWs and a COD in a Gas Flow.....	187
3.5.1	Light Combustion Wave	188
3.5.2	Combustion Wave Supported Due to Thermal Radiation Transfer.....	191
3.5.3	Continuous Optical Discharge in a Gas Flow	192
3.5.4	Optical Discharge in a Gas-Vapor Keyhole.....	202
3.6	Laser Plasmatron and Deposition of Films	204
3.6.1	Physical Processes in Optical Plasmatrons.....	204
3.6.2	High-Pressure Plasmatron	206
	References	208

4 Properties and Mechanisms of Deep Melting of Materials by a cw Laser Beam	211
4.1 Physical Processes Proceeding Upon Deep Melting of Fixed Samples	213
4.1.1 The Thermal Deep-Melting Model	213
4.1.2 Mechanical Limit of Laser Beam Penetration into Liquid	215
4.1.3 Peculiarities of Deep Laser Beam Penetration into Liquid	221
4.2 Thermal Deep Penetration Melting Model for a Moving Sample	224
4.2.1 Physical Processes in Welding of Materials	224
4.2.2 Deep Melting of Various Materials	229
4.2.3 Thermal Efficiency of Laser Welding	231
4.3 Hydrodynamical Processes During Deep Laser-Beam Penetration into Solids	237
4.3.1 Experimental Study of Material Melt Flows	237
4.3.2 Models of the Hydrodynamic Flow Upon Deep Melting	243
4.3.3 Influence of Laser Radiation Polarization and Shield Gas on Laser Welding Properties	245
4.3.4 Role of Shield Gases in Deep Melting of Metals	248
4.4 Models of a Gas-Vapor Keyhole of Finite Size	252
4.4.1 Thermal Deep-Melting Model with a Gas-Vapor Keyhole of Finite Diameter	252
4.4.2 Self-Consistent Stationary Laser Welding Model	254
4.4.3 Stability of a Cylindrical Gas-Vapor Keyhole	261
4.4.4 Instability of the Leading Edge of a Keyhole	267
4.4.5 Melt Pool Instability	269
4.5 Remote and Hybrid Welding of Metals	270
4.5.1 Features of Laser-Arc Welding of Metals	270
4.5.2 Remote Welding of Metals	274
4.5.3 Influence of Laser Radiation Quality on Laser Welding	276
References	283
5 Physics of Remote and Gas-Assisted Cutting with Lasers	287
5.1 Mechanism of Remote Cutting with cw Lasers	288
5.1.1 Physics of Melt Removal in Drilling of Vertical Plates	288
5.1.2 Drilling of Horizontal Plates	292
5.1.3 Self-Consistent Drilling Model	293
5.1.4 Thermally Thick Limit	294
5.1.5 Remote Cutting	296
5.1.6 Experimental Techniques and Results	298
5.1.7 Oscillatory Type of Remote Cutting	300
5.1.8 Comparison of Calculated and Experimental Results	301
5.1.9 Disruption of Cutting Operation	303

5.2	Properties of Gas-Assisted Cutting	304
5.2.1	Gas Dynamics in Laser Cutting	305
5.2.2	Numerical Studies of Gas Dynamics	309
5.2.3	Mechanisms of Melt Removal	313
5.2.4	Instabilities and Nonstationary Mechanisms of Melt Removal	317
5.2.5	Modelling of Melting Front and Melt Removal in Gas-Assisted Cutting of Metals	320
5.2.6	Properties and Efficiency of Gas-Assisted Cutting	325
5.2.7	Beam Polarization	329
5.2.8	Multiple Reflections	335
5.3	Physical Processes in Laser Cutting with an Oxygen Jet	336
5.3.1	Model of Stationary Cutting of Steel in an Oxygen Jet	339
5.3.2	Instability of Laser Cutting in the Oxygen Atmosphere	340
5.3.3	Experimental Studies of High-Quality Laser Cutting of Thick Mild Steels with Oxygen Assist Gas	342
	References	343
6	Interaction of Pulsed Laser Radiation with Materials	345
6.1	Physics of Pulsed Laser Ablation and Deposition of Films	346
6.1.1	Initial Stage	348
6.1.2	Ablation to Vacuum	352
6.1.3	Ablation to Buffer Gas	353
6.1.4	Comparison with Experiments	355
6.1.5	Ablation Efficiency	361
6.1.6	Ablation of Materials Irradiated by Ultrashort Laser Pulses	363
6.2	Modelling of Synthesis of Nanoparticles Upon Pulse Laser Vaporization	365
6.2.1	Diffusion Model	367
6.2.2	Results and Discussion	370
6.2.3	Erosion Jet	373
	References	377
7	Pulsed Surface Plasma	379
7.1	Pulsed Optical Breakdown Near a Surface	379
7.1.1	Nonstationary Thermal Breakdown	380
7.1.2	Quasi-Stationary Breakdown	381
7.1.3	Optical Breakdown in a Target Vapor Jet	382
7.1.4	Two-Dimensional and Nonequilibrium Effects in the Pulsed Breakdown	385
7.2	Nonequilibrium Mechanisms of the Pulsed Breakdown	388

7.3	Dynamics of a Plasma Plume and its Interaction with a Laser Beam	395
7.3.1	Propagation Mechanisms of the Surface Plasma	396
7.3.2	Propagation of a Laser-Supported Detonation Wave in the Surrounding Gas	399
7.3.3	Reflecting Properties of a Plasma Plume	406
7.3.4	Numerical Modelling of a Pulsed Optical Discharge	407
7.3.5	Modeling Results	408
7.3.6	Expansion Mechanisms of Plasmas	409
7.3.7	Plasma Transparency and Transmission Coefficient	413
7.3.8	Comparison with Experiments	415
7.4	Plasma Processes in Material Vapors	418
7.4.1	Plasma Processes on a Target Surface	420
7.4.2	Plasma Processes During Vaporization of Metals in Air	424
7.4.3	Plasma Phenomena During the Deep Penetration of a Laser Beam into a Sample and Breakdown on Microdroplets	427
	References	432
8	Physics of the Damage and Deep Melting of Metals by Laser Pulses	435
8.1	Qualitative Hydrodynamical Model of Laser-Induced Melt Removal	435
8.1.1	Removal on a Melt from a Shallow Pool	436
8.1.2	Fountain Wave Regime	437
8.1.3	Liquid Splash Regime	439
8.1.4	Specific Damage Energy	441
8.1.5	Numerical Modelling of Metal Removal from a Shallow Melt Pool	443
8.2	Experimental Studies of the Interaction of Millisecond Laser Pulses with Materials	447
8.2.1	Experimental Study of Shallow Damage of Materials	447
8.2.2	Deep-Penetration Keyhole Damage by a Single Pulse from a Neodymium Laser	450
8.3	Damage of Materials by Microsecond and Ultrashort Laser Pulses	451
8.3.1	Experimental Studies of the Damage of Metals by Pulsed CO_2 Laser Radiation	451
8.3.2	Material Processing by Ultrashort Pulses	454
8.3.3	Theoretical Models of Formation of Deep Keyholes in Metals by CO_2 Laser Radiation	458
8.3.4	Waveguide Regime	460

8.4	Physics of Deep Melting of Metals by Pulsed Radiation	463
8.4.1	Pulsed Welding	463
8.4.2	Control of the Deep Penetration Melting Process	466
	References	468
9	Interaction of Repetitively Pulsed Laser Radiation with Materials	471
9.1	Modeling of Thermal Processes During Repetitively Pulsed Irradiation of a Sample Surface	472
9.1.1	Features of Thermal Processes and Phase Transitions During Repetitively Pulsed Laser Irradiation ...	473
9.1.2	Thermal Model of Metal-Surface Hardening by Repetitively Pulsed Laser Radiation	477
9.2	Thermal Model of Deep Melting of Metals by Repetitively Pulsed Laser Radiation with Low Off-Duty Ratio	480
9.2.1	Thermal Model of Deep Melting of Moving Samples by Repetitively Pulsed Radiation	480
9.2.2	Thermal Model of Metal Welding with a Pulsed Laser with Low Off-Duty Ratio	482
9.3	Physical Processes During Welding of Metals by Repetitively Pulsed Laser Radiation with High Off-Duty Ratio	487
9.3.1	Theoretical Model	487
9.3.2	Experimental Studies	493
9.3.3	Dynamics of a Weld Pool Upon Repetitively Pulsed Irradiation	495
9.4	Drilling and Cutting of Metals by Repetitively Pulsed Radiation	501
9.4.1	Properties and Mechanism of Metal Cutting by Repetitively Pulsed CO ₂ Laser Radiation	501
9.4.2	Gas Assisted Laser Cutting of Metals by Repetitively Pulsed Radiation	504
9.4.3	Modelling of the Instability of Deep Laser-Beam Penetration into a Moving Target	506
9.5	Damage and Remote Cutting of Metals by a Repetitively Pulsed Laser	509
9.5.1	Formulation of the Problem	509
9.5.2	Experimental Results	510
9.5.3	Numerical Model	512
9.5.4	Comparison of Numerical Calculations with Experiment ...	515
9.5.5	Remote Damage of Metals by Radiation from High-Average-Power Lasers	518

9.5.6	Remote Cutting Model for Thick Plates.....	519
9.5.7	Thin Plates	523
References	526
Index	529