

Contents

| | |
|---|-----------|
| Introduction | 1 |
| 1 Fundamentals of Short and Ultrashort Pulse Laser Ablation | 5 |
| 1.1 Energy Absorption and Redistribution | 5 |
| 1.2 Material Removal Processes | 9 |
| 1.3 Material Vapor and Plasma | 10 |
| 1.4 Summary Description of the Ablation Process | 11 |
| 2 Short and Ultrashort Pulse Laser Drilling | 13 |
| 2.1 Techniques for Drilling Process Investigation | 13 |
| 2.1.1 Post-Process Shape Survey | 14 |
| 2.1.2 On-line Depth Measurement | 15 |
| 2.1.3 Direct Observation Techniques | 16 |
| 2.2 Model Description of the Drilling Process | 17 |
| 2.3 Influence of the Processing Conditions on the Drilling Behavior | 22 |
| 2.3.1 Drilling under Reduced Ambient Pressure | 22 |
| 2.3.2 Drilling at High Repetition Rates | 23 |
| 2.4 Current State of Knowledge | 25 |
| 3 In-situ Imaging of the Drilling Process | 27 |
| 3.1 Model System for Drilling in Opaque Materials | 27 |
| 3.2 In-situ Imaging System | 30 |
| 4 Hole Shape Formation | 33 |
| 4.1 Hole Shape Evolution | 33 |
| 4.1.1 Phases of the Drilling Process | 35 |
| 4.1.2 Statistical Variations of the Drilling Process | 37 |
| 4.2 Influence of the Process Parameters | 43 |
| 4.2.1 Fluence and Pulse Energy | 43 |
| 4.2.2 Focus Position | 47 |
| 4.2.3 Wavelength | 51 |
| 4.2.4 Pulse Duration | 57 |
| 4.3 Three Phase Model of the Deep Drilling Process | 64 |

Contents

| | |
|---|------------|
| 5 Hole Shape Formation Processes | 67 |
| 5.1 Influence of the Ambient Pressure | 68 |
| 5.1.1 Drilling Behavior under Different Ambient Pressure Conditions . . | 69 |
| 5.1.2 Hole Interior and Particle Debris Distribution | 74 |
| 5.2 Interaction at High Repetition Rates | 77 |
| 5.3 Analysis of the Laser-generated Plasma | 83 |
| 5.3.1 Temporal Evolution of the Plasma Expansion | 84 |
| 5.3.2 Depth-dependence of the Plasma Expansion | 86 |
| 5.4 Light Propagation inside a Laser-drilled Hole | 87 |
| 5.5 Conclusion | 94 |
| Summary and Outlook | 95 |
| Appendix | 99 |
| A Simulation of Ultrashort Pulse Absorption in Copper | 101 |
| B Simulation of Ultrashort Pulse Absorption in Silicon | 103 |
| C Comparison of BPM and FDTD Simulation | 109 |
| References | 113 |
| Publications in Peer-reviewed Journals | 131 |
| Conference Contributions | 133 |