

CONTENT

Notation	ix
Abbreviations	ix
Symbols	x
Abstract	xiii
Zusammenfassung	xv
1 Introduction	1
1.1 Additive layer manufacturing (ALM).....	1
1.1.1 Wire-feed processes	2
1.1.1.1 Laser beam processes (WF-L-Beam)	3
1.1.1.2 Arc beam processes (WF-A-Beam)	4
1.1.1.3 Electron beam processes (WF-E-Beam)	5
1.1.2 Powder-bed and powder-feed processes	5
1.2 Material science review	7
1.2.1 Elemental titanium	7
1.2.1.1 Physical properties	7
1.2.1.2 Crystal structure and diffusion	7
1.2.1.3 Hardening mechanisms	10
1.2.2 Titanium Ti-6Al-4V	11
1.2.3 Additive layer manufactured Ti-6Al-4V.....	16
1.3 Laser welding review.....	18
1.3.1 General considerations	18
1.3.2 Laser welding of Ti and Ti-6Al-4V	19
1.3.3 Solidification and grain growth	19
1.4 Work Plan	21
1.4.1 Motivation	21
1.4.2 Objectives	23
1.4.3 Structure	24
2 Experimental details	25
2.1 ALM processes used	25
2.1.1 Wire-feed processes	25
2.1.2 Powder-bed and powder-feed processes	27
2.2 Microstructural characterization	28
2.3 Post build-up heat treatments	29
2.4 Mechanical characterization	29
2.4.1 Static tensile tests	30
2.4.2 High cycle fatigue tests	31
2.4.3 Fracture toughness tests	32
2.5 Sample manufacturing	32
2.5.1 Wire-feed ALM samples	32
2.5.2 Powder-bed and powder-feed ALM samples	34

3 Results	35
3.1 Wire-feed ALM of Ti-6Al-4V.....	35
3.1.1 Single beads: microstructural properties	35
3.1.1.1 Morphology and microstructure	35
3.1.1.2 Hardness	40
3.1.1.3 Dimensions	42
3.1.1.4 Influence of process parameters: general considerations.....	43
3.1.1.5 Influence of process parameters: microstructure	44
3.1.1.6 Influence of process parameters: hardness.....	47
3.1.1.7 Influence of process parameters: dimensions	48
3.1.2 Multi bead builds: microstructural properties	49
3.1.2.1 Morphology and microstructure	49
3.1.2.2 Chemical analysis	53
3.1.2.3 Hardness	53
3.1.3 Multi bead builds: mechanical properties.....	56
3.1.3.1 Static tensile properties: WF-L-Beam material.....	56
3.1.3.2 Static tensile properties: WF-A-Beam material	62
3.1.3.3 Static tensile properties: comparison of WF-L-Beam and WF-A-Beam material ..	64
3.1.3.4 High cycle fatigue properties: WF-L-Beam material.....	65
3.1.3.5 High cycle faigue properties: WF-A-Beam material	65
3.1.3.6 Fracture toughness properties: WF-L-Beam material.....	66
3.2 Powder-bed and powder-feed ALM of Ti-6Al-4V.....	68
3.2.1 Multi bead builds: microstructural properties	68
3.2.1.1 Morphology and microstructure	68
3.2.1.2 Chemical analysis	70
3.2.2 Multi bead builds: mechanical properties.....	70
3.2.2.1 Static tensile properties.....	70
3.2.2.2 High cycle fatigue properties	74
3.2.2.3 Fracture toughness properties	74
4 Discussion	77
4.1 Wire-feed ALM of Ti-6Al-4V.....	77
4.1.1 Single beads: microstructural properties	77
4.1.1.1 Microstructure: general considerations	77
4.1.1.2 Microstructure: influence of process parameters.....	78
4.1.1.3 Hardness: general considerations.....	82
4.1.1.4 Hardness: influence of process parameters	84
4.1.1.5 Dimensions: general considerations.....	85
4.1.1.6 Dimensions: influence of process parameters	86
4.1.2 Multi bead builds: microstructural properties	88
4.1.2.1 Morphology and microstructure	88
4.1.2.2 Hardness	90
4.1.3 Multi bead builds: mechanical properties.....	93
4.1.3.1 Static tensile and high cycle fatigue properties	93
4.1.3.2 Fracture toughness properties	96
4.2 Powder-bed and powder-feed ALM of Ti-6Al-4V.....	97
4.2.1 Multi bead builds: microstrucrural properties.....	97
4.2.2 Multi bead builds: mechanical properties.....	98
4.2.2.1 Static tensile and high cycle fatigue properties	98
4.2.2.2 Fracture toughness properties	100

4.3	Final discussion and conclusions.....	102
4.3.1	Single beads	102
4.3.2	Multi bead builds	102
5	Summary and outlook	106
6	References	107
A.1	Appendix: wire-feed ALM of Ti-6Al-4V	120
A.1.1	Single beads: microstructural properties	120
A.1.1.1	Light microscopy pictures.....	120
A.1.1.2	Actual / expected deposition ratio diagrams	121
A.1.1.3	Hardness diagrams	121
A.1.1.3.1	Influence of laser power.....	121
A.1.1.3.2	Influence of welding speed.....	123
A.1.1.3.3	Influence of wire-feed speed factor	124
A.1.1.3.4	Influence of energy input per unit length	127
A.1.1.4	Dimension diagrams	127
A.1.1.4.1	Influence of laser power.....	127
A.1.1.4.2	Influence of welding speed.....	129
A.1.1.4.3	Influence of wire-feed speed factor	131
A.1.2	Multi bead builds: microstructural properties	133