

Contents

Nomenclature	i
1 Introduction	1
1.1 Background and motivation	1
1.2 Thesis objectives and outline	2
2 Characterisation of mechanical behaviour at large deformations	5
2.1 Elastic and plastic deformation	6
2.2 Ductile damage and failure	8
3 Fundamentals of continuum mechanics based material modelling	13
3.1 Kinematics	13
3.2 Balance equations	14
3.2.1 Mechanical balance equations	14
3.2.2 Thermodynamic balance equations	15
3.3 Constitutive equations	16
3.3.1 General remarks	16
3.3.2 Theory of isotropic linear elasticity	16
3.4 Stress state characterisation	18
3.4.1 Stress invariants	18
3.4.2 Stress triaxiality	19
3.4.3 LODE angle and LODE parameter	21
3.4.4 Plane strain and plane stress	24
4 Temperature and rate dependent plasticity at finite strains	27
4.1 Framework of finite thermo-viscoplasticity	27
4.1.1 Decomposition of kinematic variables	27
4.1.2 Hypo-elastic formulation	29
4.2 A finite thermo-viscoplasticity model for a wide temperature range	30
4.2.1 Temperature dependent VON MISES yield criterion	30
4.2.2 Nonlinear isotropic hardening with temperature dependence	33
4.2.3 Flow rule with strain rate and temperature sensitivity	38
4.2.4 Summary	43
5 Energy transformation behaviour and thermo-mechanical coupling	45
5.1 Energy storage and dissipation of mechanical work into heat	45
5.1.1 TAYLOR-QUINNEY approximation	46
5.1.2 Thermo-mechanically consistent approach based on enhanced rheological elements	47

5.2	Numerical solution and implications of thermo-mechanical coupled problem	49
6	Verification and validation of the finite thermo-viscoplasticity model for a wide range of temperatures	51
6.1	Parameter identification and model evaluation for various metal alloys	51
6.1.1	Test database	51
6.1.2	Identification of model parameters	52
6.1.3	Discussion of verification results	54
6.1.4	Comparison of the proposed theory to other thermo-viscoplasticity models	59
6.2	Finite element analysis of simultaneous hot/cold forging of a shaft . .	60
6.2.1	Process description	61
6.2.2	FE modelling	62
6.2.3	Discussion of simulation results	65
7	Modelling stress state dependent ductile damage and failure	71
7.1	Modelling approaches	71
7.2	Stress state dependent phenomenological failure models	72
7.2.1	JOHNSON-COOK model	72
7.2.2	BAO-WIERZBICKI model	73
7.2.3	HOSFORD-COULOMB model	76
7.3	Failure modelling for nonproportional load paths	83
7.3.1	Definition of proportional and nonproportional loading and its effects on the stress state	84
7.3.2	Damage indicators	87
7.3.3	Analytical failure analysis for nonproportional loading scenario	88
7.4	Continuum damage model including stress state dependence	92
7.4.1	Framework of continuum damage mechanics	93
7.4.2	Modelling of nonlinear damage evolution	96
7.4.3	Damage initiation and failure criterion	97
8	Localisation phenomenon and regularisation methods	99
8.1	Softening, instability and localisation	99
8.2	Demonstration example of a bar under uniaxial tension	100
8.3	Regularisation methods	103
8.3.1	Crack-band model and viscous regularisation	103
8.3.2	Integral nonlocal formulation	105
8.3.3	Gradient enhanced damage approach	108
9	Parameter identification, verification and validation of the nonlocal ductile damage model under multiaxial loading	113
9.1	Characterisation of microalloyed steel sheets under multiaxial loading	113

9.2	Parameter identification and model verification for a wide range of stress states	117
9.2.1	Finite element modelling	117
9.2.2	Parameter identification	119
9.2.3	Discussion of verification results	124
9.3	Mesh objectivity and comparative assessment of nonlocal approaches	127
9.4	Model validation	129
9.4.1	Combined shear-tension specimen	129
9.4.2	Square tube under axial crushing	133
10	Summary and outlook	137
A	Appendix	141
A.1	Tensor calculations	141
A.2	Kinematics and stress states for basic loading conditions	143
A.3	POISSON ratio for elasto-plastic materials	150
A.4	Displacement functions for constant nominal and logarithmic strain rates	151
	Bibliography	153