

Contents

Notation	ix
1 General introduction	1
1.1 Constant velocity joint	2
1.2 Manufacturing route	3
1.3 Modelling strategy	5
2 General phase transformation theory	7
2.1 Thermodynamic calculations	8
2.1.1 Pure substances	8
2.1.2 Random substitutional solutions	8
2.1.3 Sub-lattice models	10
2.1.4 Limitations of the method	11
2.2 Classic kinetic theory	11
2.2.1 Classical theory for homogeneous nucleation	11
2.2.2 Overall transformation kinetics	12
2.2.3 Martensitic transformations	15
2.2.4 Transformation diagrams and critical cooling rates	16
2.3 Process models	18
2.4 Phases considered	20

3 Austenitisation and deformation	23
3.1 Austenitisation	24
3.1.1 Phenomenology	24
3.1.2 Nucleation and growth	24
3.1.3 Alloying elements	25
3.1.4 Modelling austenitisation from different microstructures	26
3.2 Effects of deformation	29
3.2.1 Effect of deformation on kinetics	29
3.2.2 Grain deformation	30
3.2.3 Deformation of pearlitic steel: effects on ferrite and cementite	30
4 Tempering of carbon steel	33
4.1 Tempering of martensite	34
4.2 Modelling of tempering and hardness prediction	35
4.2.1 Hardness predictions used in process models	35
4.2.2 Prediction of hardness evolution	36
5 Advanced empirical modelling methods	39
5.1 Artificial neural networks (ANN)	40
5.2 Gaussian Processes (GP)	43
5.3 Comparison between ANN and GP	44
5.4 ANN applied to materials science	45
6 Thermal cycle during induction hardening	47
6.1 Introduction	48
6.2 Analytical model for temperature evolution	48
6.2.1 Induction Heating	50
6.2.2 Water Spray Quenching	50
6.2.3 Computer program	50
6.2.4 Results and possible improvements	51
6.3 Finite difference method	52

6.3.1	Notation used in both symmetries	53
6.3.2	The Crank-Nicholson method applied to a plate	54
6.3.3	The Crank-Nicholson method applied to a cylinder	56
6.3.4	Implementation of the model and improvements introduced . .	57
6.4	Comparison with measurements	59
6.5	Conclusions	62
7	Model for austenitisation of hypoeutectoid steels	63
7.1	Introduction	64
7.1.1	Austenitisation of a hypoeutectoid steel	64
7.2	Mathematical modelling of austenitisation	65
7.2.1	Characterisation of the microstructure	65
7.2.2	Quantitative measurements	68
7.3	Mathematical modelling of austenitisation	70
7.3.1	Nucleation of austenite	70
7.3.2	Diffusion-controlled growth of austenite in steel	72
7.3.3	Transformation of pearlite	74
7.3.4	Transformation of ferrite	76
7.4	Comparison with experimental results	77
7.4.1	Experimental procedure	77
7.5	Applications	88
7.6	Conclusions	88
8	Effect of deformation on austenitisation	91
8.1	Introduction	92
8.2	Experimental procedure	92
8.2.1	Sample material	92
8.2.2	Dilatometric tests	93
8.2.3	Microscopy and chemical analysis	94
8.3	Results and discussion	95

8.3.1	Effect of deformation on austenitisation	95
8.3.2	Effect of deformation on spheroidisation	97
8.3.3	Effect of heating rate	101
8.3.4	Effect of microstructure	101
8.3.5	Combined effect	106
8.4	Conclusions	114
9	Modelling the decomposition of austenite	115
9.1	Introduction and structure of the model	116
9.2	Prediction of decomposition of austenite	117
9.2.1	Classical overall transformation kinetics for isolated reactions .	117
9.2.2	Randomly nucleated simultaneous reactions	119
9.2.3	Boundary nucleated simultaneous reactions	120
9.2.4	Formation of allotriomorphic ferrite	122
9.2.5	Formation of pearlite	124
9.2.6	Formation of Widmanst�tten ferrite	125
9.2.7	Formation of bainite	127
9.2.8	Formation of martensite	129
9.2.9	Determination of critical temperatures for transformation .	130
9.3	Implementation of the model	131
9.4	Analysis of model predictions	133
9.4.1	Effect of austenite grain size	134
9.4.2	Effect of carbon content	134
9.4.3	Effect of substitutional solutes	135
9.5	Conclusions	139
10	Model of low temperature tempering	141
10.1	Introduction	142
10.2	Experimental procedure	142
10.3	Training the neural network	144

10.3.1	Database and variables	144
10.3.2	The model	144
10.3.3	Significance of the input variables	145
10.4	Using the model to make predictions	146
10.5	Determination of activation energy for tempering	147
10.6	Activation energy for diffusion of carbon in martensite	151
10.7	Conclusions	152
11	Summary and suggestions for future work	153
11.1	Application to a process	154
11.2	Summary of the present work	160
11.3	Suggestions for future work	161

