

Table of content

List of symbols	<i>xi</i>
List of abbreviations	<i>xiv</i>

General Introduction

OBJECTIVES	4
GENERAL OUTLINE	5
REFERENCES	7

Chapter I : Theoretical Background

I.1 PHASE STABILITY	10
I.1.1 PHASES AND CRYSTAL LATTICES	10

Table of content

I.1.2 INFLUENCE OF TEMPERATURE, CHEMICAL COMPOSITION AND APPLIED STRESS	12
I.2 STACKING FAULT ENERGY	21
I.2.1 DESCRIPTION OF A STACKING FAULT	21
I.2.2 INFLUENCE OF VARIOUS PARAMETERS ON THE STACKING FAULT ENERGY	22
<i>I.2.2.1 Chemical composition</i>	22
<i>I.2.2.2 Temperature</i>	25
<i>I.2.2.3 Austenite grain size</i>	26
I.2.3 EFFECT OF THE STACKING FAULT ENERGY ON THE DEFORMATION MODES	28
<i>I.2.3.1 Dislocations and partial dislocations</i>	28
<i>I.2.3.2 Mechanical twins</i>	30
<i>I.2.3.3 Mechanically-induced martensitic transformation</i>	31
<i>I.2.2.4 Relationship between stacking fault energy and deformation mode</i>	32
I.3 MECHANICALLY-INDUCED MARTENSITIC TRANSFORMATION	33
I.3.1 CRYSTALLOGRAPHIC MECHANISMS	33
<i>I.2.3.1 Transformation into ε-martensite</i>	33
<i>I.2.3.2 Formation of α'-martensite</i>	35
<i>I.2.3.3 Orientation relationships</i>	38
I.3.2 TRIP EFFECT AND VARIANT SELECTION	42
I.4 CONCLUSION	44
REFERENCES	45

Chapter II : Materials and Experimental Procedures

II.1 MATERIALS	55
II.1.1 STEELS 301LN AND 304	56
II.1.2 STEELS Mn15 AND Mn20	57
II.2 EXPERIMENTAL PROCEDURES	58
II.2.1 CHARACTERISATION OF THE MICROSTRUCTURE	58
<i>II.2.1.1 Preparation of the surface</i>	<i>58</i>
<i>II.2.1.2 Metallography of the undeformed microstructure</i>	<i>58</i>
<i>II.2.1.3 Phase proportions and compositions</i>	<i>60</i>
<i>II.2.1.4 Transmission electron microscopy</i>	<i>66</i>
<i>II.2.1.5 Orientation imaging microscopy</i>	<i>68</i>
<i>II.2.1.6 Measurements of defect-free austenite</i>	<i>70</i>
II.2.2 THERMO-MECHANICAL PROCESSES	72
<i>II.2.2.1 Uniaxial tensile tests</i>	<i>72</i>
<i>II.2.2.2 Rolling</i>	<i>74</i>
<i>II.2.2.3 Rotary swaging</i>	<i>75</i>
<i>II.2.2.4 Stress states</i>	<i>77</i>
<i>II.2.2.5 Annealing treatments</i>	<i>80</i>
REFERENCES	82

Table of content

**Chapter III : Influence of the Chemical
Composition and Annealing Conditions
on the Microstructure of Fe-Mn-Si-Al
Steels**

III.1 INTRODUCTION	85
III.2 MATERIALS AND EXPERIMENTAL PROCEDURES	88
III.3 RESULTS	89
III.4 DISCUSSION	96
III.4.1 COMPARISON BETWEEN EXPERIMENTAL RESULTS AND CALCULATED PSEUDO-BINARY PHASE DIAGRAMS	96
III.4.2 INFLUENCE OF THE CHEMICAL COMPOSITION AND THE ANNEALING CONDITIONS ON THE AUSTENITE STABILITY	104
III.4.3 INFLUENCE OF THE CHEMICAL COMPOSITION AND THE ANNEALING CONDITIONS ON THE STACKING FAULT ENERGY	106
III.4.4 INFLUENCE OF THE AL AND SI CONTENT ON THE MECHANICAL PROPERTIES	110
III.5 CONCLUSION	111
REFERENCES	113

Table of content

Chapter IV : Evolution of Grain Size in Rolled and Annealed Austenitic Stainless Steel

IV.1 INTRODUCTION	115
IV.2 THEORETICAL BACKGROUND	117
IV.2.1 RECOVERY	118
IV.2.2 RECRYSTALLISATION	119
IV.2.3 RETRANSFORMATION	120
IV.2.4 GRAIN GROWTH	123
IV.3 MATERIALS AND EXPERIMENTAL PROCEDURES	127
IV.4 RESULTS	130
IV.4.1 MICROSTRUCTURES	130
<i>IV.4.1.1 Initial states</i>	<i>130</i>
<i>IV.4.1.2 Deformed states</i>	<i>131</i>
<i>IV.4.1.3 Annealed states</i>	<i>133</i>
IV.4.2 KINETICS OF ACTIVE PHENOMENA	140
IV.5 DISCUSSION	147
IV.5.1 RECRYSTALLISATION IN SAMPLES ROLLED AT 200°C AND ANNEALED	148
IV.5.2 RECRYSTALLISATION AND RETRANSFORMATION IN SAMPLES ROLLED AT 20°C AND ANNEALED	151

Table of content

IV.5.3 GRAIN GROWTH IN SAMPLES ROLLED AT 20°C AND ANNEALED OR IN SAMPLES ANNEALED WITHOUT ROLLING	159
IV.5.4 SELECTION OF THERMO-MECHANICAL PROCESSES TO INCREASE AND TO REFINES THE GRAIN SIZE	161
IV.6 CONCLUSION	163
REFERENCES	165

Chapter V : Mechanisms of Strain- induced Phase Transformations in Fe-Ni-Cr and Fe-Mn-Al-Si Steel Grades

V.1 INTRODUCTION	167
V.2 MATERIALS AND EXPERIMENTAL PROCEDURES	169
V.3 RESULTS	172
V.3.1 STRAIN-INDUCED PHASE TRANSFORMATIONS IN FE-MN-SI-AL STEELS	172
V.3.2 STRAIN-INDUCED PHASE TRANSFORMATIONS IN FE-NI-CR STAINLESS STEELS	186
V.3.3 PARTICULAR CASES OF PHASE TRANSFORMATIONS IN FE-MN-SI-AL STEELS	191

Table of content

V.4 DISCUSSION	195
V.4.1 MECHANISMS OF STRAIN-INDUCED PHASE TRANSFORMATIONS	196
<i>V.4.1.1 Transformation of austenite into ε-martensite</i>	<i>196</i>
<i>V.4.1.2 Formation of α'-martensite</i>	<i>197</i>
V.4.2 CRYSTALLOGRAPHIC ASPECTS OF STRAIN-INDUCED PHASE TRANSFORMATIONS	200
<i>V.4.2.1 Variant selection during strain-induced phase transformations of stainless steels</i>	<i>202</i>
<i>V.4.2.2 Variant selection during strain-induced phase transformations of Fe-Mn-Si-Al steels</i>	<i>210</i>
V.4.3 EMERGENCE OF SECONDARY VARIANTS	216
V.5 CONCLUSION	221
REFERENCES	225

Chapter VI : Influence of Strain-induced Phase Transformations on the Mechanical Properties of Fe-Ni-Cr and Fe-Mn-Si-Al Steel Grades

VI.1 INTRODUCTION	229
--------------------------	------------

Table of content

VI.2 MATERIALS AND EXPERIMENTAL PROCEDURES	233
VI.3 RESULTS	236
VI.3.1 MECHANICAL PROPERTIES AND STRAIN-INDUCED PHASE TRANSFORMATIONS DURING TENSILE STRAINING	236
VI.3.2 EVOLUTION OF PHASE PROPORTIONS DURING COLD ROLLING OR ROTARY SWAGING IN FE-NI-CR STAINLESS STEELS	252
VI.4 DISCUSSION	254
VI.4.1 ROLE OF THE DIFFERENT PHASES IN THE MECHANICAL PROPERTIES	254
<i>VI.4.1.1 Influence of ferrite and austenite on the mechanical properties in Fe-Mn-Si-Al steels</i>	<i>254</i>
<i>VI.4.1.2 Effect of strain-induced phase transformation on the mechanical properties</i>	<i>257</i>
VI.4.2 INFLUENCE OF THE CHEMICAL COMPOSITION ON THE MECHANICAL PROPERTIES AND ON THE STRAIN-INDUCED TRANSFORMATIONS	261
VI.4.3 INFLUENCE OF THE TEMPERATURE ON THE MECHANICAL PROPERTIES AND ON THE STRAIN-INDUCED TRANSFORMATIONS IN FE-NI-CR STAINLESS STEELS	265
VI.4.4 INFLUENCE OF THE AUSTENITE GRAIN SIZE ON THE MECHANICAL PROPERTIES AND ON THE STRAIN-INDUCED TRANSFORMATIONS	266
VI.4.5 INFLUENCE OF THE STRESS STATE ON THE PHASE TRANSFORMATIONS IN FE-NI-CR STAINLESS STEELS	268

Table of content

VI.5 CONCLUSION	273
REFERENCES	276

Conclusion and Prospects

GENERAL CONCLUSION	281
PROSPECTS	285
REFERENCES	289

List of symbols

α :	Alpha ferrite (BCC)
α' :	Alpha prime martensite (BCC)
ε :	Epsilon martensite (HCP)
ε :	True strain
$\varepsilon^{lat.}$:	Lattice strain
ε_{eq} :	Equivalent deformation
ε_u :	True strain at maximal load
$\varepsilon_y^{lat.}$:	Lattice yield strain
γ :	Austenite (FCC)
γ_b :	Grain boundary energy
σ :	True stress
σ_γ :	Austenite yield strength
σ_{eq} :	Equivalent stress
σ_u :	True stress at maximal load
$\sigma_y^{lat.}$:	Lattice yield strength
τ :	Characteristic timescale depending on the grain growth velocity
A_s :	Austenite starting temperature
c, c_1, c_2 :	Proportionality constants
$d^{lat.}$:	Lattice parameter
$d_0^{lat.}$:	Stress-free lattice parameter
D_i :	Initial diameter
D_f :	Final diameter

Table of content

$E^{lat.}$	: Lattice Young modulus
$f(t)$	: Relative amount of transformation (between 0 and 1)
GS	: Grain size
ΔG_{crit}	: Minimum difference of free energies between two phases to initiate the transformation
$\Delta G_{ch,T}$	: Difference of chemical free energies between two phases at a temperature T
I	: Number of boundaries intercept
$I(twins)$	: Number of twin boundaries intercept
k	: Geometric constant
L	: Length of the intercepted segments
LP	: Lode parameter
M	: Grain boundary mobility
M_d	: Temperature above which the austenite is stable and no mechanically-induced martensitic transformation can take place
$M_{d(30)}$	: Temperature at which 30% of tensile true strain induces a transformation of 50% of the austenite into martensite
M_s	: Martensite start temperature, corresponding to the appearance of thermal martensite
M_s^σ	: Temperature where the stress required to initiate the martensitic transformation reaches the austenite yield strength
MLI_t	: Mean linear intercept (including the twin boundaries)
MLI	: Mean linear intercept (without the twin boundaries)
n	: Avrami exponent
n	: Grain growth exponent

Table of content

n :	Work-hardening coefficient
ND :	Normal direction
$n_{incr.}$:	Incremental work-hardening coefficient
P :	Driving pressure for grain growth
$p(twins)$:	Proportion of twin boundaries
$\overline{R}$:	Grain boundary mean curvature radius
R_1, R_2 :	Grain boundary main curvature radii
RD :	Rolling direction
SFE_1 :	Stacking fault energy at temperature T_1
S_s :	Starting section
S_f :	Final section
TD :	Transverse Direction
t :	Time
t_0 :	Time at the beginning of the transformation
t_s :	Starting thickness
t_f :	Final thickness
T_0 :	Temperature where the free energy of two phases involved in a transformation are identical
T_N :	Néel temperature
T_m :	Melting temperature
TR :	Stress triaxiality ratio
U :	Mechanical free energy
U^{max} :	Maximum of mechanical free energy
v :	Grain boundary velocity

List of Abbreviations

at.% :	Atomic percent
BCC :	Body-centered cubic
Cr _{eq} :	Chromium equivalent
CPP :	Close-packed plane
CRSS :	Critical resolved shear stress
EBSD :	Electron back-scattered diffraction
FCC :	Face-centered cubic
FSD :	Fore scatter detector
HAGB :	High angle grain boundary
HCP :	Hexagonal close-packed
IPF :	Inverse pole figure
KS :	Kurdjumov-Sachs
LAGB :	Low angle grain boundary
ND :	Neutron diffraction
Ni _{eq} :	Nickel equivalent
NW :	Nishiyama-Wasserman
OIM :	Orientation imaging microscopy
SEM :	Scanning electron microscope
SFE :	Stacking fault energy
TEM :	Transmission electron microscope
ToF :	Time of flight
TRIP :	Transformation-induced plasticity
XRD :	X-ray diffraction
wt.% :	Weight percent