

University of Wollongong - Research Online

Thesis Collection

Title: In-situ studies of delta-ferrite/austenite phase transformation in low carbon steels

Author: Salar Niknafs

Year: 2007

Repository DOI:

Copyright Warning

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site.

You are reminded of the following: This work is copyright. Apart from any use permitted under the Copyright Act 1968, no part of this work may be reproduced by any process, nor may any other exclusive right be exercised, without the permission of the author. Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material.

Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Unless otherwise indicated, the views expressed in this thesis are those of the author and do not necessarily represent the views of the University of Wollongong.

Research Online is the open access repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

2007

In-situ studies of delta-ferrite/austenite phase transformation in low carbon steels

Salar Niknafs
University of Wollongong

Follow this and additional works at: <https://ro.uow.edu.au/theses>

University of Wollongong

Copyright Warning

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site.

You are reminded of the following: This work is copyright. Apart from any use permitted under the Copyright Act 1968, no part of this work may be reproduced by any process, nor may any other exclusive right be exercised, without the permission of the author. Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material.

Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Unless otherwise indicated, the views expressed in this thesis are those of the author and do not necessarily represent the views of the University of Wollongong.

Recommended Citation

Niknafs, Salar, In-situ studies of delta-ferrite/austenite phase transformation in low carbon steels, MEng-Res thesis, University of Wollongong, 2007. <http://ro.uow.edu.au/theses/36>

NOTE

This online version of the thesis may have different page formatting and pagination from the paper copy held in the University of Wollongong Library.

UNIVERSITY OF WOLLONGONG

COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

IN-SITU STUDIES OF
DELTA-FERRITE/AUSTENITE
PHASE TRANSFORMATION
IN LOW CARBON STEELS

A thesis submitted in fulfilment of the
requirements for the degree of

Master of Engineering by Research

From

University of Wollongong

by

Salar Niknafs BEng(Hon), MEng(Prac)

Materials Engineering

2007

CERTIFICATION

I, Salar Niknafs, declare that this thesis, submitted in fulfilment of the requirements for the award of Honours Master of Engineering by Research, in the Materials Engineering Discipline, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Salar Niknafs

August 2007

ACKNOWLEDGEMENTS

“If I have been of service, if I have glimpsed more of the nature and essence of ultimate good, if I am inspired to reach wider horizons of thought and action, if I am at peace with myself, it has been a successful day.”

-- Alex Noble

I would like to acknowledge my supervisor Professor Rian Dippenaar, not only for his academic support, but for ensuring many a successful day. Many thanks to my colleagues, Sima Aminorroaya, Mark Reid and Dominic Phelan for offering me valuable advice throughout my research; and to my friends Behzad Fatahi and Hani Zahiri for their thoughtful criticisms.

Most importantly, I want to express my gratitude to my family, without whom this work could not have been achieved.

ABSTRACT

During continuous casting of steel, the delta-ferrite to austenite phase transition occurs following solidification in the meniscus region of the solidifying strand. It is of great industrial significance to gain a better understanding of the nature and mechanism of this reaction because product quality is in large measure determined by events occurring during and shortly following solidification. Moreover, the exact way in which delta-ferrite transforms to austenite may influence the subsequent transformation of austenite to ferrite, by which much of the mechanical properties of the steel is determined.

Relatively little attention has been devoted to the delta-ferrite to austenite phase transition in the past, in part because of the difficulty of making in-situ observations at the high temperature at which this phase transition occurs. The recent development of high-temperature laser-scanning confocal microscopy has provided new opportunities to observe in-situ high temperature phase transformations and this technique has been employed in the present study.

In order to limit grain boundary pinning by alloying elements and alloy compounds during growth of delta-ferrite grains and their influence on the δ -to- γ phase transition, the solid-state phase transformation was studied in low-carbon iron-carbon alloys. Experimental observations of the effect of cooling rate on the δ/γ phase transformation are discussed in terms of three different morphologies that have been observed.

At low cooling rates the newly formed austenite phase that nucleated at triple points grow by an advancing planar interface but at higher cooling rates the transformation occurs by a massive kind of transformation. The mechanisms of grain boundary movement also been investigated. Two types of grain boundary movement, continuous motion and staggered motion have been observed. Quantitative analysis of grain boundary movement show that at low cooling rates grain boundaries are stationary for a few seconds after the initiation of the phase transformation and then they progress exponentially. Computer simulations have been used in an attempt to better explain the experimental observations.

TABLE OF CONTENTS

CHAPTER 1- INTRODUCTION	1
CHAPTER 2- LITERATURE SURVEY	4
2.1 Continuous casting	4
2.2 Phase Transitions in Iron based Alloys	5
2.2.1 Solidification	6
2.2.2 Delta-ferrite to austenite phase transition	7
2.3 Oscillation Marks	8
2.3.1 Description of Phenomena	9
2.3.2 Abnormal Grain Growth and Oscillation Marks	10
2.4 Theories on Grain Growth.....	14
2.4.1 Normal Grain Growth.....	14
2.4.1.1 The Burke and Turnbull Analysis.....	14
2.4.1.2 The Smith Analysis.....	15
2.4.1.3 Mean Field Theories.....	17
2.4.1.3.1 Mean Field Theories based on the drift velocity term.....	19
2.4.1.3.2 Mean Field Theories based on diffusion term.....	21
2.4.1.4 The Rhines and Craig analysis	21
2.4.2 Abnormal Grain Growth	24
2.4.2.1 The Gladman Analysis	25
2.4.2.2 The Hillert Analysis.....	25
2.4.2.3 The Thompson Analysis.....	27
2.4.3 Summary of grain growth theories	28
2.5 The effect of specimen thickness on the grain size.....	28
2.6 Previous work on the delta-ferrite to austenite phase transition.....	30
CHAPTER 3 – EXPERIMENTAL PROCEDURE.....	38
3.1 Review of Experimental Techniques.....	38
3.1.1 MICRESS, phase field software	38

3.1.2 Laser Scanning Confocal Microscopy.....	38
3.2 Preparation of Confocal Microscopy Samples.....	40
3.3 Procedure of the high temperature CSLM experiments.....	41
3.4 Typical delta-ferrite microstructure.....	44
3.5 Qualitative observations of phase transformation Morphologies	45
CHAPTER 4 - RESULTS AND DISCUSSION.....	48
4.1 Group 1 - 5°C/min cooling rate	48
4.1.1 Motion of delta-ferrite grain boundaries.....	48
4.1.1.1 Stop-start motion (staggered motion) of delta-ferrite grain boundaries	49
4.1.1.2 Continuous motion of delta-ferrite grain boundaries.....	51
4.1.1.3 Quantitative analysis of triple-point movement.....	52
4.1.4 The delta-ferrite to austenite phase transformation morphology	57
4.1.5 Simulation of the δ -ferrite/ γ phase transformation at a cooling rate of 5°C/min.....	62
4.2 Group 1 - 10°C/min cooling rate	69
4.3 Group 1 - 15°C/min cooling rate	73
4.4 Group 1 - 30°C/min cooling rate	75
4.5 Group 1 - 40°C/min cooling rate	78
4.6 Group 1 - 70°C/min cooling rate	79
4.7 Group 2.....	82
4.8 Preserving the delta-ferrite structure at room temperature.....	83
4.9 Grain growth observations	85
CHAPTER 5- CONCLUSIONS.....	89
APPENDIX 1	91
APPENDIX 2	93
Second phase particles and grain boundary pinning	93
APPENDIX 3	94
MICRESS simulation of carbon concentration gradient and its evolution during the δ -ferrite/ γ phase transformation at the cooling rate of 5°C/min	94

REFERENCES	100
------------------	-----

Table of figures

FIGURE 1 SLAB CASTING PROCESS.....	4
FIGURE 2 IRON-CARBON PHASE DIAGRAM.....	6
FIGURE 3 (A) SOLIDIFICATION DEFECTS [6] (B) OSCILLATION MARKS [7]	7
FIGURE 4 SCHEMATIC OF INITIAL SOLIDIFICATION NEAR MENISCUS [14]	9
FIGURE 5 ABNORMALLY LARGE AUSTENITE GRAINS ALONG OSCILLATION MARKS [11]	11
FIGURE 6 TRANSVERSE CRACK AT THE BASE OF AN OSCILLATION MARK ON THE AS CAST TOP SURFACE OF A 0.20%C STEEL SLAB. ETCHED IN HOT HCL [11].....	12
FIGURE 7 GRAIN GROWTH OF AUSTENITE GRAINS DURING CONTINUOUS COOLING. THE SPECIMENS WERE REMELTED AT 1580°C, COOLED TO A GIVEN TEMPERATURE AT THE RATE OF 0.28°C/S AND THEN WATER QUENCHED [36]	12
FIGURE 8 SCHEMATIC ILLUSTRATION OF EVENTS IN THE FORMATION OF SURFACE CRACKS RELATED TO BLOWN GRAINS DURING CASTING [11]	13
FIGURE 9 GRAIN GROWTH AS A CHANGE IN GAIN SIZE DISTRIBUTION AS A FUNCTION OF TIME [41].....	17
FIGURE 10 MECHANISMS OF GRAIN GROWTH ACCORDING TO THE MEAN FIELD THEORY [41]	18
FIGURE 11 GAIN SIZE DISTRIBUTION IN TWO AND THREE DIMENSIONAL SYSTEMS [42]	20
FIGURE 12 PLOT OF $M_v S_v$ VS N_v FOR STEADY STATE GRAIN GROWTH IN ALUMINIUM [46]	23
FIGURE 13 PLOT OF GRAIN VOLUME ($1/N_v$) AGAINST TIME OF ANNEALING FOR ALUMINIUM SHOWING A LINEAR RELATIONSHIP [46]	24
FIGURE 14 SCHEMATIC REPRESENTATION OF THE TYPE OF GRAIN GROWTH AND AVERAGE GRAIN SIZE DEPENDING ON THE VALUE OF Z [42]	27
FIGURE 15 MAXIMUM GRAIN SIZE ATTAINABLE BY GRADUAL GRAIN GROWTH IN HIGH PURITY ALUMINIUM, AS A FUNCTION OF SPECIMEN THICKNESS SHOWING “SPECIMEN THICKNESS EFFECT”. (A) SPECIMENS NOT ETCHED BEFORE ANNEALING. EMPTY CIRCLE: SPECIMEN EXTREMELY DEEPLY ETCHED BEFORE ANNEALING [52].....	29
FIGURE 16 MIGRATION PRODUCED BY UNEQUAL SURFACE-FREE ENERGIES [52]	30
FIGURE 17 FORMATION OF AUSTENITE AT A Δ -FERRITE TRIPLE POINT AND AT A Δ -GRAIN BOUNDARY. THE SAMPLES WERE COOLED AT A RATE OF 2°C/MIN COOLING RATE [32]	31
FIGURE 18 SCHEMATIC DIAGRAM OF THE NUCLEATION AND GROWTH OF THE AUSTENITE PHASE IN THE Δ -FERRITE MATRIX AT COOLING RATES <7°C/MIN [32].....	31
FIGURE 19 COMPARISON OF THE CARBON DISTRIBUTION AT THE FRONT OF Δ/Γ INTERPHASE BOUNDARIES BETWEEN DURING Δ/Γ AND DURING Γ/Δ PHASE TRANSFORMATION [32]	32
FIGURE 20 COMPARISON OF THE TEMPERATURE PROFILE AND CONSTITUTIONAL SUPERCOOLING AT THE FRONT OF Δ/Γ INTER-PHASE BOUNDARIES DURING Δ TO Γ TRANSFORMATION AND DURING Γ TO Δ TRANSFORMATION [32]	33
FIGURE 21 DELTA-FERRITE SUB-BOUNDARY MICROSTRUCTURE OBSERVED WITH LSCM [54]	34
FIGURE 22 TRANSFORMATION OF DELTA-FERRITE TO AUSTENITE IN SI-KILLED STEEL [4]	35
FIGURE 23 THE OBSERVED STARTING AND FINISHING TEMPERATURE OF THE Δ/Γ TRANSFORMATION FOR THE LPS AND MPS SAMPLES AT VARIOUS COOLING RATES [55]	36
FIGURE 24 THE OBSERVED AND CALCULATED TEMPERATURES OF THE Δ/Γ PHASE TRANSFORMATION. (A) LOW COOLING RATE; (B) HIGH COOLING RATE [55].....	37
FIGURE 25 SCHEMATIC REPRESENTATION OF THE LSCM CHAMBER	39
FIGURE 26 SCHEMATIC REPRESENTATIONS OF THE CSLM HOLDER AND CRUCIBLE	40
FIGURE 27 SAMPLE PREPARATION.....	41
FIGURE 28 SURFACE TOPOGRAPHY OF A SLAB SAMPLE CONTAINING 3 OSCILLATION MARKS [57]	42
FIGURE 29 HEAT TREATMENT PROCEDURE AT THE COOLING RATE OF 70°C/MIN	44
FIGURE 30 DELTA-FERRITE STRUCTURE CONSISTING GBS AND SUB-GBS.....	45

FIGURE 31 AUSTENITE STRUCTURE COOLED FROM DELTA-FERRITE REGION, CONSISTING OF Γ -GBS AND PRIOR Δ -FERRITE GB GROOVES	45
FIGURE 32 DISAPPEARANCE OF SMALL GRAINS. TEMPERATURE= 1492°C. THE SNAPSHOTS WERE TAKEN WITHIN 92 SECONDS (THE NUMBERED PHOTOS SCHEMATICALLY REPRESENT THE GRAINS AND THEIR ASSOCIATED GRAIN- BOUNDARIES).....	46
FIGURE 33 DEVELOPMENT OF THERMAL GROOVES ALONG THE GRAIN BOUNDARIES AT HIGH TEMPERATURES.....	47
FIGURE 34 SCHEMATIC REPRESENTATION OF A THERMAL GROOVE AROUND GRAIN BOUNDARIES [4]	47
FIGURE 35 HEAT TREATMENT PROCEDURE	48
FIGURE 36 STOP-START MOTION OF DELTA-FERRITE TRIPLE POINT	49
FIGURE 37 GEOMETRIC PARAMETERS ASSOCIATED WITH BOUNDARIES ADJOINING A TRIPLE JUNCTION [59]	50
FIGURE 38 GRAIN BOUNDARY ANCHORING AT A NOTCH [52]	50
FIGURE 39 CONTINUOUS MOTION OF DELTA-FERRITE TRIPLE POINT BEFORE Δ -FERRITE/ Γ PHASE TRANSFORMATION	51
FIGURE 40 MOVEMENT OF THE DELTA-FERRITE TRIPLE POINT, BOTH STAGGERED AND CONTINUOUS MOTION ARE EVIDENT.....	53
FIGURE 41 PROGRESSION OF THE DELTA-FERRITE TRIPLE POINT DURING THE PERIOD OF CONTINUOUS MOVEMENT AT THE COOLING RATE OF 5°C/MIN	54
FIGURE 42 DELTA-FERRITE STRUCTURE CONSISTING OF 3 GRAINS AND A TRIPLE POINT. DASH-LINE REPRESENTS DELTA-FERRITE GRAIN BOUNDARY GROOVES WHILE THE SOLID LINES ARE GRAIN BOUNDARIES. (A) DELTA-FERRITE TRIPLE POINT BEFORE CONSISTENT CONTINUOUS MOVEMENT (B) CONSISTENT CONTINUOUS MOVEMENT (C) RAPID MOVEMENT	55
FIGURE 43 UNPINNING EFFECT OF DELTA-FERRITE TRIPLE POINTS LEADING TO RAPID MOTION OF THE DELTA-FERRITE TRIPLE POINT.....	56
FIGURE 44 CONTINUOUS MOVEMENT OF A DELTA-FERRITE TRIPLE POINT IN THE DIRECTION AO	56
FIGURE 45 CHANGE IN THE DIRECTION OF A DELTA-FERRITE TRIPLE POINT FROM AO TO BO DIRECTION, 23 SECONDS AFTER THE START OF CONTINUOUS MOTION.....	57
FIGURE 46 THE DELTA-FERRITE TO AUSTENITE PHASE TRANSFORMATION MORPHOLOGY AT A COOLING RATE OF 5°C/MIN	58
FIGURE 47 THE FIRST STAGE OF THE Δ -FERRITE/ Γ PHASE INTERFACE DEVELOPMENT DURING THE GROWTH OF THE NEWLY-FORMED AUSTENITE NUCLEUS	59
FIGURE 48 THE SECOND STAGE OF THE Δ -FERRITE/ Γ PHASE INTERFACE DEVELOPMENT AS THE AUSTENITE GRAIN GROWS.....	60
FIGURE 49 THE PROGRESSION OF THE Δ -FERRITE/ Γ PHASE TRANSFORMATION INTERFACE AT A COOLING RATE OF 5°C/MIN	60
FIGURE 50 PROPAGATION VELOCITY OF Γ INTO THE Δ -FERRITE MATRIX DURING THE Δ -FERRITE/ Γ PHASE TRANSFORMATION AT A COOLING RATE OF 5°C/MIN	61
FIGURE 51 THE PROPAGATION VELOCITY OF Γ INTO THE Δ -FERRITE MATRIX DURING THE SECOND STAGE OF AUSTENITE PROPAGATION AT 5°C/MIN COOLING RATE	62
FIGURE 52 MICRESS SIMULATION OF THE Δ -FERRITE/ Γ PHASE TRANSFORMATION SHOWING EARLY GROWTH OF THE AUSTENITE GRAINS THAT NUCLEATED ON A DELTA-FERRITE GRAIN BOUNDARY.....	63
FIGURE 53 MICRESS SIMULATION OF THE PROPAGATION OF AUSTENITE PHASE INTO THE Δ -FERRITE MATRIX.	64
FIGURE 54 MICRESS SIMULATION OF CARBON CONCENTRATION GRADIENT DURING THE Δ -FERRITE/ Γ PHASE TRANSFORMATION AT 5°C/MIN COOLING RATE	67
FIGURE 55 IRON-CARBON PHASE DIAGRAM, HORIZONTAL LINES SUGGEST THAT DURING THE Δ / Γ PHASE TRANSITION, THE INITIAL DELTA-FERRITE NUCLEI FORMS WITH A HIGH CARBON CONTENT. AS THE FURTHER COOLING CONTINUOUS THE CARBON CONTENT DIFFERENCE BETWEEN THE DELTA-FERRITE AND AUSTENITE DECREASES	68
FIGURE 56 THE DELTA-FERRITE TO AUSTENITE PHASE TRANSFORMATION MORPHOLOGY AT A COOLING RATE OF 10°C/MIN	69
FIGURE 57 THE POSITION OF THE PHASE TRANSFORMATION INTERFACE DURING Δ -FERRITE TO AUSTENITE PHASE TRANSFORMATION.....	70

FIGURE 58 PROGRESSION OF THE Δ -FERRITE/ Γ INTERFACE OF A GRAIN THAT NUCLEATED ON AN AUSTENITE GRAIN BOUNDARY AND GROWS INTO THE Δ -FERRITE MATRIX. COOLING RATE: 10°C/MIN.....	71
FIGURE 59 THE PROPAGATION VELOCITY OF THE Δ -FERRITE INTERFACE (REFER TO FIGURE 58).....	71
FIGURE 60 THE PROGRESSION OF AUSTENITE ALONG THE DELTA-FERRITE GBS AND INTO THE Δ -FERRITE MATRIX	72
FIGURE 61 PROGRESSION OF THE Δ/Γ INTERFACE ALONG THE DELTA-FERRITE GBS AND INTO ITS MATRIX (NOTE THE ZERO POINT OF THE MEASUREMENT SHOWN IN FIGURE 60).....	72
FIGURE 62 VELOCITY OF THE Δ/Γ INTERFACE ALONG THE GRAIN BOUNDARY AND INTO THE MATRIX.....	73
FIGURE 63 THE DELTA-FERRITE TO AUSTENITE PHASE TRANSFORMATION MORPHOLOGY AT A COOLING RATE OF 15°C/MIN	74
FIGURE 64 (A) STABILIZED AUSTENITE STRUCTURE AND GROOVES OF A PRIOR Δ -FERRITE GROWING BOUNDARY (B) GROWTH OF WIDMANSTÄTTEN FERRITE PLATES FROM THE AUSTENITE GRAIN BOUNDARIES	75
FIGURE 65 NUCLEATION OF AUSTENITE FROM A DELTA-FERRITE TRIPLE POINT AND GRAIN BOUNDARIES	76
FIGURE 66 THE DELTA-FERRITE TO AUSTENITE PHASE TRANSFORMATION MORPHOLOGY AT A COOLING RATE OF 30°C/MIN	76
FIGURE 67 FORMATION AND STABILIZATION OF AUSTENITE FINGER-LIKE STRUCTURES AT THE COOLING RATE OF 30°C/MIN	77
FIGURE 68 STABILIZATION OF AUSTENITE FINGER-LIKE STRUCTURES AT THE COOLING RATE OF 30°C/MIN	78
FIGURE 69 THE DELTA-FERRITE TO AUSTENITE PHASE TRANSFORMATION MORPHOLOGY AT A COOLING RATE OF 40°C/MIN (DASHED LINE SHOWS THE DELTA-FERRITE GRAIN BOUNDARY GROOVE)	78
FIGURE 70 THE NUCLEATION OF THE DELTA-FERRITE FROM THE AUSTENITE TRIPLE JUNCTIONS AND GBS AT A COOLING RATE OF 70°C/MIN	79
FIGURE 71 THE DELTA-FERRITE TO AUSTENITE PHASE TRANSFORMATION MORPHOLOGY AT A COOLING RATE OF 70°C/MIN	80
FIGURE 72 ANOTHER EXAMPLE OF THE FORMATION OF AUSTENITE ISLAND-LIKE STRUCTURES AT A COOLING RATE OF 70°C/MIN.....	80
FIGURE 73 FORMATION OF AUSTENITE SWORD-LIKE STRUCTURES AT A COOLING RATE OF 70°C/MIN	81
FIGURE 74 AUSTENITE TRIPLE POINT AT EQUILIBRIUM FOLLOWING THE Δ/Γ PHASE TRANSFORMATION	81
FIGURE 75 (A) INITIATION OF AUSTENITE TO ALPHA-FERRITE PHASE TRANSFORMATION (B) TYPICAL STRUCTURE OF WIDMANSTÄTTEN COLONY	82
FIGURE 76 CONTINUOUS MOVEMENTS OF DELTA-FERRITE GRAIN BOUNDARIES AND TRIPLE POINT AT THE COOLING RATE OF 15°C/MIN ON THIN SAMPLE	83
FIGURE 77 PRESERVED DELTA-FERRITE STRUCTURE IN ROOM TEMPERATURE SHOWING ABNORMAL GRAIN GROWTH OF SOME GRAINS.....	84
FIGURE 78 SCHEMATIC ILLUSTRATION OF OXIDE FORMATION DURING THE PROGRESSIVE OR DIRECT AIR INSERTION [61]	85
FIGURE 79 A DELTA-FERRITE GRAIN WITH A DIAMETER OF ABOUT 800 μ M (ASSUMING A CIRCULAR MORPHOLOGY).....	85
FIGURE 80 AN AUSTENITE GRAIN WITH A DIAMETER OF ABOUT 500 μ M (ASSUMING A CIRCULAR MORPHOLOGY).....	86
FIGURE 81 FORMATION OF WIDMANSTÄTTEN PLATES AT THE AUSTENITE GRAIN BOUNDARIES.....	87
FIGURE 82 AUSTENITE STRUCTURE AND GROOVES OF THE PRIOR Δ -FERRITE SHOWING AN APPROXIMATELY SAME GRAIN SIZE (REPEATED)	87
FIGURE 83 AUSTENITE GRAIN BOUNDARIES AS WELL AS THE PRIOR DELTA-FERRITE GRAIN BOUNDARIES, OBSERVED AT THE COOLING RATE OF 70°C, SHOWING NO SIGNIFICANT CHANGE IN THE SIZE OF GRAINS AFTER THE Δ/Γ PHASE TRANSFORMATION (REPEATED).....	88
FIGURE 84 THE RADII OF CURVATURE (R_1 AND R_2) OF THE GRAINS BETWEEN WHICH THE ATOMS ARE TRANSFERRED [37].....	91

<i>FIGURE 85 A SCHEMATIC OF THE FORMATION OF A DIMPLE DURING GRAIN BOUNDARY BYPASS OF A PARTICLE [64]</i>	<i>93</i>
---	-----------