

BAINITE IN STEELS

BAINITE IN STEELS

Transformations, Microstructure
and Properties

SECOND EDITION

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Preface

Computational metallurgy has grown rapidly over the last twenty years and the subject has been embraced by industry with remarkable enthusiasm, resulting in close collaborations and long term partnerships between industry and academic research laboratories. No longer are alloys designed from experience alone but calculations are used to reduce the task and to introduce creativity. There are now numerous examples of profitable commercial products resulting from the application of this type of research.

The fact that bainitic steels have featured prominently in this kind of metallurgy is a testimony to the depth of understanding that has been achieved. The highest ever combinations of strength and toughness (1600 MPa, 130 MPa m^{1/2}) have been obtained in bainitic steels invented using theory alone. Optically visible bainite has been obtained under conditions where the diffusion distance of an iron atom is just 10⁻¹⁷ m. Automobiles have become safer because of the incorporation of bainite-containing strong steels to protect against sideways collisions. Gigantic magnetic fields have been used to stimulate bainite. New tungsten-containing creep-resistant bainitic steels, which can be used without post-weld heat treatment have now been in service for more than four years. Experimental techniques invented to characterise the nucleation of bainite on ceramic particles have been emulated in other fields of metallurgy.

Atomic resolution has shown that like ordinary bainite, substitutional solutes simply do not diffuse during the growth of acicular ferrite. The mechanism of carbide precipitation in bainite is better understood; but wouldn't it be nice if the displacements due to precipitation could be characterised?

The focus has shifted from stress to strain-affected transformation. Indeed, it has been proposed that 'there is no mechanism by which plastic strain can retard reconstructive transformation. Likewise, only displacive transformations can be mechanically stabilised.' This provides a simple way of establishing the atomic mechanism of transformation. The proposal has not yet been contradicted.

Bainite is thriving as a material. Most of the new products based on bainite are manufactured by large steel industries. There are in addition, university spin-offs. In one case, a large company has been created to manufacture and market only bainitic steels; the company concerned is possibly unique in

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having the word 'bainite' in its title. In another case a fledgling 'dot-com' has been created to market the software useful in modelling the microstructure and properties of bainitic and other steels. A short monograph on bainite is now available in seven different languages on the world wide web.

Much has changed since the first edition of this book. There is a new clarity in the concepts associated with solid-state transformations. There is even transparency in the definition of problems which are not yet understood. To summarise, I sense real progress. It was useful therefore to write a second edition rather than just reprint the first. As with the first edition, this book is meant for all who are interested in transformations in steels or who are curious about phase changes in general.

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I dedicate this book to Anika, Maya, Narmada and Dharamshi.

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Nomenclature

a	Length of an edge crack
Δa_m	Minimum detectable increase in austenite layer thickness
\bar{A}	Mean areal intercept in stereology
Ac_3	Temperature at which a sample becomes fully austenitic during heating
Ae_3	Temperature separating the $\alpha + \gamma$ and γ phase fields for a specific alloy
Ar_3	Temperature at which an austenitic sample begins to transform to ferrite during cooling
A_f	Temperature at which the transformation to austenite is complete
A_i	Atomic weight of element i
A_s	Temperature at which the transformation to austenite begins
\bar{A}_s	Mean free slip area in statistical theory for plasticity (Kocks, 1966)
\bar{B}	Matrix representing the Bain deformation
B_d	Highest temperature at which bainite forms under the influence of an externally applied stress
B_S	Bainite-start temperature
B_σ	A temperature below which bainitic transformation is considered to be stress-assisted and above which it is considered to be strain-induced, during transformation under the influence of an externally applied stress
c	Length of an edge crack, or length of a microcrack nucleus
c_d	Diameter of a penny-shaped crack in a spheroidal particle
$c_i^{\alpha\theta}$	Concentration of element i in phase α which is in equilibrium with phase θ
c_o	Carbide thickness
C_i	Constants, with $i = 1, 2, 3 \dots$
d	Interatomic spacing along a specific crystallographic direction
\underline{d}	Vector describing the shear component of an IPS
D_α	Diffusivity of carbon in ferrite
D or D_γ	Diffusivity of carbon in austenite
D_i^α	Diffusivity of element i phase α
D_{eff}	Effective diffusion coefficient
\bar{D}	Weighted average diffusivity of carbon in austenite

Nomenclature

E	Young's Modulus
f_1	Normalised supersaturation
f_C	Activity coefficient for carbon in austenite
f^*	Attempt frequency for atomic jumps across an interface
G	Growth rate
ΔG_m	Molar Gibbs free energy
G_N	Function specifying the free energy change needed in order to obtain a detectable rate of nucleation for Widmanstätten and bainite
G_N^α	Function specifying the critical value of $\Delta G^{\gamma \rightarrow \alpha}$ at the M_s temperature
G^*	Activation free energy for nucleation, or for interfacial motion
G_O^*	Activation free energy to overcome the resistance to dislocation motion without the aid of a chemical driving force
G_1^*	Activation free energy for the growth of an embryo into a nucleus
G_2^*	Activation free energy for the transfer of atoms across the nucleus/matrix interface
G_{dd}	Free energy dissipated in the process of solute diffusion ahead of an interface
G_F	Free energy per unit area of fault plane
G_i^0	Molar Gibbs free energy of pure i
G_{id}	Free energy dissipated in the transfer of atoms across an interface
G'_{id}	Free energy term describing the maximum glide resistance of dislocations
G_s	Strain energy per mole
G_{SB}	Stored energy of
G_{SW}	Stored energy of bainite
ΔG	General term representing driving force
ΔG_{CHEM}	Chemical driving force
ΔG_m	Molar Gibbs free energy change on transformation; alternatively, the maximum molar Gibbs free energy change accompanying nucleation
ΔG_{MECH}	Mechanical driving force
ΔG_{STRAIN}	Coherency strain energy during nucleation
$\Delta G_{\gamma \rightarrow \alpha}$	Free energy change for transformation without composition change
h_α	Ledge height at the interface between α and the parent phase
H	Hardness of martensite
H_F	Hardness of tempered martensite when all excess carbon has precipitated
H_0	Hardness of virgin martensite
H_1	A function in the theory of diffusion-controlled growth

Nomenclature

$\Delta H^{\gamma\alpha}$	Enthalpy change during the $\gamma \rightarrow \alpha$ transformation
v_I	Nucleation rate per unit volume
J	Diffusion flux
k	Boltzmann constant
k_A	Constant in the Avrami equation
k_e	Equilibrium solute partitioning coefficient
k_g	Constant relating lath size to strength
k_i	Partitioning coefficient for alloying element i
k_p	Coefficient representing the strengthening effect of cementite particles; alternatively, a solute partitioning coefficient
k_e	Coefficient in an equation for the strength of tempered martensite
K_I	Stress intensification factor in fracture mechanics
K_{IC}	Critical value of K_I , a measure of the toughness of a material
K_{ISCC}	Threshold value of the stress intensity below which stress corrosion cracks do not grow at a perceptible rate
ΔK	Stress intensity range during fatigue testing
ΔK_O	Threshold value of the stress intensity range during fatigue crack growth studies
Δl_m	Maximum relative length contraction due to isothermal re-austenitisation
\bar{L}	Mean intercept length in stereology, grain size
L_S	Lower bainite start temperature
m	Paris constant in fracture mechanics
m_i	Mass fraction of element i
M	Mobility of an interface
M_d	Highest temperature at which martensite forms under the influence of an externally applied stress
M_S	Martensite start temperature
n	Time exponent in the Avrami equation
n_A	Number of atoms in an embryo involved in nucleation
n_{Fe}	Number of iron atoms per unit volume of α
n_p	Number of close-packed planes involved in the faulting process during displacive nucleation
N	Number of cycles in fatigue loading
N_v	Number of particles per unit volume
p	Péclet number (a dimensionless velocity) or autocatalytic factor
P	Pressure
\underline{P}	Matrix representing a homogeneous invariant-plane strain deformation
q	Half the increase in the thickness of austenite during one-dimensional growth
Q	Activation energy

Nomenclature

\underline{Q}	Matrix representing an inhomogeneous lattice-invariant deformation
r	Radius of a disc; alternatively, the distance ahead of a crack tip; alternatively the tip radius of a growing plate
r_1	Proof stress to ultimate tensile stress ratio
r_2	Ratio of σ_a to σ_s
r_C	Critical distance in fracture mechanics, related to K_{IC} ; alternatively, critical tip radius at which the growth of a plate ceases
r_e	Value of r_2 at the endurance limit in fatigue
\bar{r}	Mean particle radius at time t
\bar{r}_0	Mean particle radius at time zero
R	Universal gas constant; alternatively, the semi-axis of an oblate ellipsoid
R_d	Rate at which growing austenite dilutes
s	Shear component of the IPS shape deformation
\underline{S}	Deformation matrix in the crystallographic theory of martensite
S_1, S_2	Functions in the Trivedi model for the growth of parabolic cylinders
S_V	Interfacial area per unit volume
t	Time; alternatively, the thickness of a disc
t_1	Time for isothermal transformation to bainite during austempering of cast iron
t_2	Time to the beginning of carbide precipitation from austenite during austempering
t_a	Time required to reach a given fraction ξ of isothermal transformation
t_c	Time required for a sub-unit to reach a limiting size
t_d	Time required to decarburise a plate of bainite
t_i	Time interval for step i in a series of isothermal heat treatments
t_θ	Time for the precipitation of cementite from ferrite
Δt	Time interval between the nucleation of successive sub-unit during sheaf lengthening
T	Temperature
T_C	Critical Zener ordering temperature for carbon atoms in ferrite; alternatively, the temperature below which cementite can in principle precipitate in association with upper bainitic ferrite
T_h	The temperature below which the nucleation of displacive transformations first becomes possible at a detectable rate
T_i	Isothermal transformation temperature
T_F	Temperature at which accelerated cooling is stopped
T_0	Temperature at which γ and α of the same composition have the same free energy

Nomenclature

T_{0m}	As T_0 , but forcing the Zener ordering of carbon atoms in the ferrite
T'_0	As T_0 , but accounting for the stored energy of ferrite
T_M	Melting temperature
T_r	Temperature below which a midrib is found in lower bainite plates
T_R	Temperature at which rolling deformation is stopped
T_t	Transition temperature for impact toughness
T_γ	Isothermal re-austenitisation temperature
$T^{\gamma\alpha}$	Austenite to ferrite transformation temperature
v^*	Activation volume
V	Volume of a sample
V^α	Volume of phase α
V_e^α	Extended volume of phase α
V_d	Diffusion field velocity
V_i	Velocity of an interface calculated on the basis of its mobility
V_k	Velocity of an interface calculated using a solute trapping function
V_I	Volume fraction of inclusions
V_l	Plate lengthening rate
V_{max}	Maximum volume fraction
V_{max}^S	Maximum volume of a sheaf
ΔV_m	Change in molar volume on transformation
V_S	Sheaf lengthening rate
ΔV_v	Minimum detectable change in volume fraction
V_α^s	Velocity of steps in the α /parent phase interface
V_m^θ	Molar volume of phase θ
V_τ	Volume per particle
w	Thickness of a bainite sub-unit
w_i	Weight percent of element i
w_i^{sol}	Weight percent of element i , in solution
W	Width of a fracture toughness specimen for a K_{IC} test
\bar{x}	Average mole fraction of carbon in an alloy
x_m	Maximum carbon supersaturation permitted in ferrite, on thermodynamic grounds
x_α	Carbon in α at interface
x_γ	Carbon concentration in austenite
x_γ^I	Carbon concentration in austenite before the start of austenite growth
$x^{\alpha\gamma}$	Mole fraction of carbon in ferrite which is in equilibrium or paraequilibrium with austenite
$x^{\gamma\alpha}$	Mole fraction of carbon in austenite which is in equilibrium or paraequilibrium with ferrite
$x_{T'_0}$	Carbon concentration given by the T'_0 curve

Nomenclature

x_{Ae_3}	Carbon concentration given by the Ae_3 curve
x^θ	Thickness of cementite particle
x_X	Concentration of X in cementite
\bar{x}_X	Average concentration of X in cementite
$x_X^{\alpha\theta}$	Concentration of X in ferrite which is in equilibrium with cementite
y	Semi-axis of an oblate ellipsoid
Y	Compliance function in fracture mechanics; alternatively, a constant in the theory of thermally activated dislocation motion
z	Coordinate normal to the interface plane; alternatively, a constant in the theory of thermally activated dislocation motion
z_d	Effective diffusion distance
Z	Position of the interface along coordinate z .
α	Allotriomorphic or idiomorphic ferrite which forms by reconstructive transformation
α_1	One-dimensional parabolic thickening rate constant
β	Constant in weld metal inclusion formation theory; alternatively, an autocatalytic factor
γ	Austenite
Γ	Capillarity constant
δ_b	Boundary thickness
Δ	Uniform dilatation accompanying transformation; alternatively, the average distance between neighbouring particles in tempered martensite
θ	Cementite
ϵ_1	Average transverse thickness of dislocation cell structure in martensite
κ	Mean % planar misfit between inclusion and ferrite
λ	Interledge spacing; alternatively an intersite jump distance during diffusion
μ	Shear modulus
μ_i	Chemical potential of element i
ν	Poisson's ratio
ρ	Density
ρ_A	Spacing of close-packed planes
ρ_d	Dislocation density
τ	Incubation time before the growth of an individual particle begins during isothermal transformation, or before a detectable degree of overall transformation. Alternatively, the shear stress resolved along the shear direction
τ_0	Resistance to dislocation motion
τ_μ	Athermal resistance to dislocation motion

Nomenclature

κ	Percent planar matching during epitaxial nucleation
ψ	Constant in weld metal inclusion formation theory
σ	Applied stress
σ_a	Cyclic stress amplitude in a fatigue test
σ_C	Critical stress in fracture mechanics, related to K_{IC} ; alternatively, solid solution strengthening due to carbon
σ_F	Stress necessary for the propagation of cleavage fracture
σ_{Fe}	Strength of pure annealed iron
σ_g	Strengthening due to grain boundaries
σ_N	Normal stress on the habit plane
σ_p	Work of fracture, per unit area of crack surface
σ_r	Stress as a function of the distance r ahead of the crack tip
σ_s	Saturation value of σ_{iy} in a fatigue test
σ_{SS}	Solid solution strengthening due to substitutional solutes
σ_{iy}	Instantaneous flow stress at any particular stage of a test
σ_y	Yield stress or proof stress in monotonic loading tests
$\sigma_{\theta\alpha}$	θ/α interface free energy per unit area
σ_0	Intrinsic strength of martensite, not including microstructural strengthening
Ω	Volume per atom
Ω_{Fe}	Volume of an atom of Fe in α
Ω_c	Volume of a molecule of Fe_3C less $3\Omega_{Fe}$
ξ	Volume fraction, or volume fraction divided by the equilibrium or some other limiting volume fraction
ξ_a	A specific value of ξ
ζ	Uniaxial dilatation normal to the habit plane
ASM	American Society for Metals
ASTM	American Society for Testing Materials
BCC	Body-centred cubic
BCT	Body-centred tetragonal
CE	Carbon equivalent
FATT	Fracture assessed ductile-brittle transition temperature
FCC	Face-centred cubic
HAZ	Heat-affected zone of welded joints
HREM	High-resolution transmission electron microscopy
HSLA	High-strength low-alloy (steels)
HV	Vickers Hardness
IIW	International Institute for Welding
IPS	Invariant-Plane Strain shape change
KS	Kurdjumov-Sachs
LEFM	Linear-Elastic-Fracture-Mechanics
NW	Nishiyama-Wasermann

Nomenclature

p.p.m.	Parts per million by weight
SCR	Stress corrosion cracking resistance
SSAW	Self-Shielded Arc Weld
TRIP	Transformation-Induced Plasticity
TTT	Time-Temperature-Transformation diagram
ULCB	Ultra-low carbon bainitic steel
UTS	Ultimate tensile strength

Note: The term *residual austenite* refers to the austenite that exists at the reaction temperature during transformation to bainite, whereas the term *retained austenite* refers to the austenite which remains untransformed after cooling the specimen to ambient temperature.