Design and Characterization of Ultrafine-Grained Ferritic and Nanostructured Bainitic Steels Processed by Electropulsing Technique

Thesis submitted in partial fulfilment for the
Award of Degree

Doctor of Philosophy

by

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CERTIFICATE

It is certified that the work contained in the thesis titled ***"Design and Characterization of Ultrafine-Grained Ferritic and Nanostructured Bainitic Steels Processed by Electropulsing Technique"*** by ***Debabrata Bhuyan*** has been carried out under our supervision and this work has not been submitted elsewhere for a degree.

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I, ***Debabrata Bhuyan***, certify that the work embodied in this thesis is my own bonafide work and carried out by me under the supervision of ***Dr. Rampada Manna*** and ***Prof. G.V.S Sastry*** from ***July 2017*** to ***August 2023***, at the ***Department of Metallurgical Engineering***, Indian Institute of Technology (BHU), Varanasi. The matter embodied in this thesis has not been submitted for the award of any other degree/diploma. I declare that I have faithfully acknowledged and given credits to the research workers wherever their works have been cited in my work in this thesis. I further declare that I have not willfully copied any other's work, paragraphs, text, data, results, *etc*., reported in journals, books, magazines, reports dissertations, theses, *etc*., or available at websites and have not included them in this thesis and have not cited as my own work.

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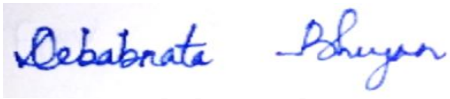

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List of Symbols

Υ	Shear strain
φ	Angle of internal channel
ψ	Outer arc of curvature
N	Number of passes
ε_N	Equivalent strain after N passes
ε_{vM}	Equivalent von Mises strain
σ_y	Yield stress
σ_i	Friction stress
K_y	Strength coefficient
d	Grain size
γ	Austenite
$V_{\gamma f}$	Volume fraction of filmy retained austenite
$V_{\gamma b}$	Volume fraction of blocky retained austenite
$V_{\alpha b}$	Volume fraction of bainite
σ_{Fe}	Frictional strength of pure iron
σ_{SS}	Solid solution strengthening from substitutional elements
σ_c	Strengthening contribution due to carbon
t_b	Thickness of bainite plate
ρ	Dislocation density
$\bar{x}$	Alloy average carbon concentration
x_b	Carbon concentration of the bainitic ferrite
W_f	Work done during passage of electric current
μ	Magnetic susceptibility
I	Current density
V	Volume of nucleus
σ_2	Electrical conductivities of nucleating phases
I_e	Nucleation rate in a current carrying system
I_0	Nucleation rate of the current-free system
D	Diffusivity
λ	Atomic jump distance
ΔW_0	Gibbs energy change in the current-free material
ΔWf	Gibbs energy change in the current carrying system
K	Boltzmann constant
T	Temperature
J	Total diffusion flux
J_e	Diffusion flux due to current
D_0	Pre-exponential diffusion factor
C_i	Vacancy concentration
Z*	Effective charge
e	Charge of electron
R_{wp}	R-weighted pattern
$y_i\,(obs)$	Observed intensity
$y_i\,(calc)$	Calculated intensity
w_i	Weight factor
χ^2	Goodness of fit

S	Scherrer constant
B	Crystallite size
ΔK_c	Broadening of a XRD peak
a_γ	Lattice parameter of austenite
w_c	Mass % of carbon
w_{Mn}	Mass % of Manganese
w_{Al}	Mass % of Aluminum
w_{Cr}	Mass % of chromium
w_{Ni}	Mass % of nickel
w_{Si}	Mass % of Si
a_α	Lattice parameter of bainite
ΔK	Peak width
K_d	Diffraction vector
M	Dislocation screening parameter
$\bar{C}$	Dislocation contrast factor
σ	True stress
ε	True strain
σ_0	Pre-stress
ε_0	Pre-strain
σ_s	Saturation stress
σ_{it}	True yield stress
ΔT	Temperature rise
Δt	Pulse period
C_p	Heat capacity
d	Density
τ_{ew}	Resolved shear stress
f_{ew}	Electron wind force
K_{ew}	Electron force coefficient
b	Burgers vector
M_d	Mobility of dislocations
N_a	Density of atoms
δ	Skin depth
f	Frequency
μ_m	Permeability
σ_{RT}^{γ}	Yield strength of the austenite at room temperature
σ_{IT}^{γ}	Yield strength of the austenite at the isothermal temperature
d^{γ}	Average austenite grain size
σ_{dis}^{γ}	Yield strength due to dislocation density in austenite
M_t	Taylor factor
μ	Shear modulus
L	Diffusion distance
Q	Activation energy
R	Universal gas constant

Abbreviations

ECAP	Equal-Channel Angular Pressing
XRD	X-Ray Diffraction Technique
TEM	Transmission Electron Microscopy
EBSD	Electron Back-Scattered Diffraction
UFG	Ultra Fine-Grained
RA	Retained Austenite
CW	Cold Working
BF	Bright Field
SEM	Scanning Electron Microscopy
BRA	Blocky Retained Austenite
FRA	Filmy Retained Austenite
EP	Electropulsing
TTT	Time-Temperature-Transformation
ASTM	American Society for Testing And Materials
SEI	Secondary Electron Imaging
IQ	Image Quality
HAGB	High Angle Grain Boundaries
LAGB	Low Angle Grain Boundaries
KAM	Kernel Average Misorientation
LCS	Low Carbon Steel
AR	As Received
DP	Diffraction Pattern
OR	Orientation Relationship
IPF	Inverse Pole Figure
GND	Geometrically Necessary Dislocations
LCD	Low Current Density
DF	Dark Field
SE	Secondary Electron
CP	Close Packed
SPD	Severe Plastic Deformation

NSM	Nanostructured Materials
SV	Surface To Volume Ratio
GNB	Geometrically Necessary Boundaries
UTS	Ultimate Tensile Strength
YS	Yield Strength
EPT	Electropulsing Technique
HV	Vickers Hardness
TRIP	Transformation Induced Plasticity
AC	Air Cooling
CCPS	Capacitor Charging Power Supply
CRO	Cathode Ray Oscilloscope
FEG	Field Emission Gun
ICDD	International Centre for Diffraction Data
PDF	Powder Diffraction File
GOF	Goodness Of Fit
WH	Williamson-Hall
MWH	Modified-Williamson-Hall
OIM	Orientation Imaging Microscopy
UE	Uniform Elongation
TE	Total Elongation
FCC	Face Cantered Cubic
FWHM	Full Width at Half Maxima
BCC	Body Cantered Cubic
NW	Nishiyama Wasserman
SIM	Strain Induced Martensite
WQ	Water Quenched