Effect of Heat Treatments and Electropulsing on the Microstructure and Mechanical Properties of Austenite Based Low-Density Steels

Thesis submitted in partial fulfillment for the
Award of Degree

Doctor of Philosophy

By

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DECLARATION BY THE CANDIDATE

I, **"Rajavarapu Pavan Kumar"**, certify that the work embodied in this thesis is my own bona fide work and carried out by me under the supervision of Prof. Rampada Manna and Prof. N. C. Santhi Srinivas from "2018" to "2025", 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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With all my heart, I dedicate this thesis to my family. Their support, belief, and sacrifices are the true foundation of this achievement.

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List of Abbreviations

UHSS	Ultra-high strength steels
AHSS	Advanced high strength steels
IF	Interstitial free steel
IF-HS	Interstitial free- high strength steel
Mild	Mild steel
BH	Bake hardenable steel
HSLA	High strength Low Alloy steel
DP	Dual phase steel
TRIP	Transformation Induced Plasticity Steel
CP	Complex phase steel
TWIP	Twinning Induced Plasticity steel
Med Mn	Medium manganese steel
MS	Martensitic steel
PHS	Press Hardened steel
QP	Quenched and Partitioned steel
RT	Room Temperature
mbar	milli bar
EDM	Electrical discharge machining
XRD	X-Ray Diffraction
SEM	Scanning Electron Microscope
FESEM	Field emission scanning electron microscope
EDS	Energy Dispersive Spectroscopy

EBSD	Electron Back Scattered Diffraction
TEM	Transmission Electron Microscope
MPa	Mega Pascal
GPa	Giga Pascal
Kg	Kilogram
Kgf	Kilogram force
kW	Kilo Watt
kHz	Kilo hertz
kN	Kilo newton
g/cm^3	Gram/ Cubic centimeter
J/mm^3	Joule / Cubic milli meter
mJ/m^2	milli joules / meter square
A/cm^2	Ampere / centimeter square
mm	millimeter
μS	micro seconds
μF	micro faraday
KV	Kilo volt
CRO	Cathode Ray Oscilloscope
EP	Electropulsing
P1	Fe-18Mn-6.5Al-0.75C
P2	Fe-18Mn-6.5Al-1.25C-2.5Ti
P3	Fe-18Mn-10Al-1C-6Ni
PD1	Fe-18Mn-6.2Al-0.75C (hot rolled)
PD1-S	Fe-18Mn-6.5Al-0.75C (solutionized)

PD1-SC	Fe-18Mn-6.5Al-0.75C (solutionized + cold rolled)
PD1-SCR	Fe-18Mn-6.5Al-0.75C(solutionized+CR+ annealed)
PD2-A	Fe-18Mn-6.5Al-1.15C-2.5Ti (solutionized)
PD3-A	Fe-18Mn-10Al-1C-6Ni (annealed)
PD3-AE	PD3-A + electro pulsed condition
PD3-AB_{30}	Fe-Mn-Al-C-Ni (in aged condition)
PD3-AB_{30}E	PD3-AB_{30} + electro pulsed condition
ARCIS	Advanced Research Centre for Iron and Steel
YS	Yield strength
UTS	Ultimate tensile strength
PE	Plastic elongation
TE	Total elongation
PSE	Tensile toughness
LAGB	Low angle grain boundaries
HAGB	High angle grain boundaries
BCC	Body centered cubic
FCC	Face centered cubic
BCC_A2	Disordered ferrite
FCC_A1	Disordered austenite
BCC_B2	Ordered bcc
Fe3C	Cementite
SFE	Stacking fault energy
MBIP	Micro band induced plasticity
HEC	Hole expansion coefficient

BA	Bending angle
Ref	Reference
Y	Year
H	Homogenization
HR	Hot rolling
HF	Hot forging
CR	Cold rolling
An	Annealing
Sol	Solutionization
WQ	Water quenching
RPM	Revolutions per minute
CCPS	Capacitor charging power supply
mA	milli amperes
km	Kock, Mecking
θ_0	Initial work hardening rate
$\frac{E}{\rho}$	specific stiffness
IQ map	Image quality map
KAM	Kernel average misorientation
ODF	Orientation distribution function
RW	Rotated W
RG	Rotated goss
VHN	Vickers hardness number
RD	Rolling direction

TD	Transverse direction
BF	Bright field
SAED	Selective area electron diffraction

List of symbols

Fe	Iron
Mn	Manganese
Al	Aluminum
C	Carbon
Ni	Nickel
Cr	Chromium
Si	Silicon
Ti	Titanium
Nb	Niobium
Co	Cobalt
Mo	Molybdenum
Cu	Copper
V	Vanadium
B	Boron
NbC	Niobium carbide
TiC	Titanium carbide
SiC	silicon carbide
K	Kelvin
°C	Degree centigrade
B2	Ordered BCC precipitate
μm	Micro meter
κ	Kappa carbide

L	Liquid
γ	Austenite
α	Ferrite
δ	Ferrite at high temperatures
β	Beta manganese
κ′	Kappa carbide with in grains
κ*	Kappa carbide at grain boundaries
γ′	Solute lean austenite phase
γ"	Solute rich austenite phase
W	Weight
t_{hkl}	Crystallite size
e_{hkl}	Micro strain
β_L	Lorentzian component of integral breadth
β_G	Gaussian component of integral breadth
λ	Wavelength
ρ_{hkl}	Dislocation density
b	Burgers vector
Å	Angstrom
E	Elastic modulus
G	Shear modulus
υ	Poisson's ratio
V_T	Transverse velocty
V_L	Longitudinal velocity

ρ	Density
σ	True stress
K	Strength parameter
ε	True strain
n	Strain hardening exponent
σ_s	Saturation stress
σ_i	True plastic stress
σ_P	Peierls stress
σ_D	Dislocation strengthening
σ_{SS}	Solid solution strengthening
σ_{GB}	Grain boundary strengthening
$\tau 0$	Shear stress
M	Taylor factor
K_B	Grain boundary locking parameter
a_0	Lattice parameter
σ_{Pr}	Precipitation strengthening
D	Diameter of particle
Cp	Heat capacity
I	Current density
(ΔG_{Chem})	Chemical free energy change
ΔG_{Inter}	Interfacial free energy change