Development of dislocation density-reliant physical models to describe the creep and flow stress response of high-temperature materials

Thesis submitted in partial fulfillment for the Award of Degree

Doctor of Philosophy

By

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Year 2024

Dedicated

To

My Beloved Parents, Elder Brother,
Elder Sister & My Future Better Half

CERTIFICATE

It is certified that the work contained in the thesis titled **"Development of dislocation density reliant physical models to describe the creep and flow stress response of high temperature materials"** by **"Nilesh Kumar"** has been carried out under my supervision and this work has not been submitted elsewhere for a degree.

It is further certified that the student has fulfilled all the requirements of Comprehensive, Candidacy and SOTA for the award of Ph.D. degree.

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DECLARATION BY THE CANDIDATE

I, **Nilesh Kumar**, certify that the work embodied in this Ph.D. thesis is my own bonafide work carried out by me under the supervision of **Dr. Surya D. Yadav** for a period from **July 2019 to December 2024 at the "Department of Metallurgical Engineering",** Indian Institute of Technology (BHU), Varanasi, India. The matter embodied in this Ph.D. 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 researchers wherever related works has been cited in this thesis. I further declare that I have not copied any other's work, paragraphs, text, data, results, *etc*., reported in journals, books, magazines, reports dissertations, thesis, *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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Nomenclature

H	internal stress generation
$\dot{\varepsilon}_0$	constant
D_d	damage due to dislocation accumulation
D_s	damage due to solute depletion
D_{ppt}	damage due to precipitate coarsening
D_N	damage due to nucleation of voids
D_{cav}	damage due to cavitation
D_{cr}	Damage due to chromium depletion
k_B	Boltzmann Constant
GBS	grain boundary sliding
IDG	intragranular deformation glide
IDC	intragranular deformation climb
ε_{GBS}	minimum creep rates due to GBS
ε_{IDG}	minimum creep rates due to IDG
ε_{IDC}	minimum creep rates due to IDC
σ	stress
σ_{appl}	applied stress
D_v	lattice diffusion coefficient
$\dot{\lambda}$	plastic multiplier
f_d	damage dissipation potential
Y	damage variable
Q_1	activation energies of GBS
Q_2	activation energies of IDG
Q_3	activation energies of IDC
R	gas constant
p	stress exponents for the mechanisms of GBS
n	stress exponents for the mechanisms of IDG
m	stress exponents for the mechanisms of IDC
T	temperature
M	Taylor factor
b	Burgers vector
γ_{sub}	low-angle subgrain boundary energy
r_p	radius of precipitate
N_p	Number density of precipitate
M_{sub}	mobility of subgrains
G	room temperature shear modulus
G_T	temperature dependent shear modulus
v_{cs}	climb velocity of static dislocation

v_{cm}	climb velocity of mobile dislocation
v_{gl}	dislocation glide velocity
ρ_m	mobile dislocation density
ρ_i	immobile dislocation density
ρ_f	forest dislocation density
ρ_{free}	free dislocation density
ρ_{dip}	dipole dislocation density
ρ_N	network dislocation density
ρ_s	static dislocation density
ρ_b	boundary dislocation density
R_{sub}	subgrain radius
$R_{sub,inf}$	limiting subgrain size
β	factor controlling the source of dislocations
h	dislocation spacing within the walls
δ	spontaneous annihilation distance
n_v	transfer coefficient of vacancies from the dislocation core to jogs
k_c	constant
D_L	lattice diffusion coffecient
D_s	solute diffusion coffecient
D_{gb}	grain boundary diffusion coffecient
D_{vp}	pipe diffusion coffecient
L_{im}	immobile dislocation spacing
M_{cl}	dislocation climb mobility
T_L	dislocation line tension
n_{slip}	number of slip systems
d_{lock}	critical distance for the dislocation lock
α	constant
Q_c	the activation energy for creep
A_N	Constant
Q_c	Activation energy for creep
$\sigma_{back,tot}$	total back stress
N	creep exponent
n_g	number of active slip plane
CDM	continuum damage mechanics
C_j	dislocation jog density
H_w	work hardening coefficient due to dislocation pile
τ_g	glide resistance for grain boundary sliding
τ_c	climb resistance for grain boundary sliding
g	grain size
h	dislocation climb distance against precipitates

ϕp	volume fraction of hard particle
λ_p	interparticle spacing
τ_D	effective shear stress
C	damage constant
Δf	Helmholtz free energy
Γ́	stacking fault factor
φ	volume fraction γ' precipitates
$\lambda_{\gamma'}$	γ' precipitate spacing
$\dot{\varepsilon}_m$	Minimum strain rate
$\dot{\varepsilon}$	strain rate
ε	strain
σ_{flow}	Flow stress
WH	work hardening
DRV	dynamic recovery
DRX	dynamic recrystallization
n	strain rate sensitivity
α_1	material constant
f_w	work hardening coefficient
g_{avg}	average grain size.
f_v	dynamic recovery coefficient
f_{drx}	dynamic recrystallization coefficient
ρ_{i-cr}	dislocation density in new dynamically recrystallized grain
s	Substructure size
σ_0	short range stress
T^{*m}	homologous temperature
$\dot{\varepsilon_{ref}}$	reference strain rate
X_{drx}	recrystallization volume fraction
l	lamellar thickness
c_0	material constant
M_{gb}	grain boundary mobility
S	dynamic globularization
λ_{mean}	mean free path
K_{L_m}	saturation rate of mobile dislocation
λ_{ms}	mean saturation-free path
δ	grain boundary thickness
D_s	self-diffusion coefficient
Q_{gb}	activation energy of grain boundary
XRD	X-ray diffraction
TEM	Transmission electron microscope

LSFE	Low stacking fault energy
HSFE	High stacking fault energy
RAFM	Reduced activation ferritic martensitic stainless steel
DA	direct aging
EBSD	electron backscattered diffraction
IPF	inverse pole figure
KAM	kernel average misorientation
w_i	weight factor for immobile dislocation
α	dislocation interaction parameter
σ_{int}	internal stress
σ_{effe}	effective stress
X	Stacking fault energy
L_p	Mean spacing of precipita
a_1	prefactor for the gliding velocity
σ_{cl}	climb stress
ϑ	Poisson's ratio
M_{sb}	mobility of subgrain boundary
γ_{sb}	surface energy of subgrain boundary
N_{vi}	number density of i^{th} precipitate
D_{vp}	core diffusion coefficient
Ω	atomic volume
c_{dip}	weight factor for dipole dislocation
D_{sd}	solute diffusion coefficient
B_{vis}	dislocation mobility
C_0	solute concentration
r_2	outer cut off radius
r_1	inner cut off radius
ε_a	relative size misfit between solute and solvent atom
c_f	weight factor for forest dislocation
v_{cg}	glide climb dislocation velocity
M_{cg}	glide climb dislocation mobility
k_{di}	Ostwald coarsening constant
r_{pi}	radius of i^{th} precipitates
M_{sb}	subgrain boundary mobility
P_{sb}	boundary pressure
M_{sb}	subgrain boundary mobility
h_b	boundary dislocation spacing
h_m	mobile dislocation spacing
DDRX	discontinuous dynamic recrystallization
SH	strain hardening

DRV	dynamic recovery
DRX	dynamic recrystallization
GDRX	geometric dynamic recrystallization
CDRX	continuous dynamic recrystallization
LAGBs	low-angle grain boundaries
HAGBs	high-angle grain boundaries
DSA	dynamic strain aging
WP	without precipitate/ precipitate free
OP-S	oxide polishing suspension
GOS	grain orientation spread
GNDs	geometrically necessary dislocations
σ_{dis}	strength contribution due to dislocations
σ_{HP}	strength contribution due to grain size
σ_{ss}	strength contribution due to solid solutions
σ_{gen}	strength contribution due to interaction among orthogonal dislocations
H_{sol}	energy barrier to dislocation motion
$\sigma_{ss,0}$	zero temperature yield stress
N_{cell}	number of atoms in the unit cell
X_i	mole fraction of the ith alloying element
δ_i	size misfit due to ith alloying element
η_i'	modulus misfit due to ith alloying element
v_0	attempt frequency
ΔG	activation energy needed to overcome the obstacles
$\sigma_{SR_{eff}}$	difference between the total flow stress and athermal stress
η	coefficient for transfer of defects into jogs
L_{climb}	length associated with elastic interactions between dislocation and defects
C_k	dislocation interaction coefficient
ρ_c	critical dislocation density for DDRX
M_{gb}	mobility of the grain boundary
Q_{gb}	activation energy for grain boundary diffusion
δ	grain boundary thickness
τ	dislocation line energy
γ_{gb}	grain boundary energy per unit area
θ_m	misorientation angle of HAGBs
Qn	activation energy for DDRX
X_{DDRX}	DDRX recrystallization fraction
v	velocity of the grain boundary
P	pressure on the grain boundary
q	shape factor
N	number of DDRX nuclei

t	time
g_{drx}	dynamic recrystallized grain size
F_{drx}	dynamic recrystallization coefficient
λ_{dis}	average dislocation distance for climb
g_{eff}	effective grain size
LR	long-range
SR	short-range
TBs	twin boundaries
ρ_{grwn}	grown dislocation density

List of Publications

1. **N. Kumar**, A.S. Joseph, P. Mehrotra, Surya D. Yadav, An improved dislocation density reliant model to address the creep deformation of reduced activation ferritic martensitic steel, **Forces in Mechanics** 9 (2022) 100117.
2. **N. Kumar**, Surya D. Yadav, Modelling the creep curves of RAFM steel employing a dislocation density reliant model, **Materials Today: Proceedings** 74 (2023) 910-915.
3. **N. Kumar**, Surya D. Yadav, Creep curve modelling of Austenitic Steel 316LN, IOP Conference Series: **Materials Science and Engineering,** IOP Publishing, 2022, p. 012022.
4. **N. Kumar**, Surya D. Yadav, Microstructure Based Flow Stress Modelling of Superalloy 718, Solid State Phenomena 353 (2023) 103-108.
5. **N. Kumar,** R.H.Buzolin, E. Shahryari, K. Pradeep, M. C. Poletti and Surya D. Yadav, A dislocation density reliant mean-field model to describe the creep response and microstructure evolution of superalloy IN-718. **Accepted in Trans. Indian Inst. Met.**.
6. **N. Kumar,** F. M.B.Ferraz, R.H.Buzolin, E. Shahryari, M. C. Poletti and Surya D. Yadav, A meso-scale model to predict flow stress and microstructure during hot deformation of precipitate-free IN718WP. **Under review**.
7. **N. Kumar** and Surya D. Yadav Creep curve modelling of Austenitic Steel 316LN. **Under review.**
8. A. S. Joseph, P. Gupta, **N. Kumar**, M. C. Poletti, and Surya D. Yadav. 2022. "An advanced dislocation density-based approach to model the tensile flow behaviour of a 64.7 Ni–31.96 Cu alloy." **Philosophical Magazine** 102 (15):1481-1504.
9. P. Mehrotra, **N. Kumar**, A. George, K. C. Sahoo, V. Ganesan, M. R. Ahmadi, S. Trivedi, and Surya D Yadav. 2022. "An advanced mean field dislocation density reliant physical model to predict the creep deformation of 304HCu austenitic stainless steel." **Materials Today Communications** 32:104128.
10. A. Kumar, **N. Kumar**, M. K. Mahto, Surya D. Yadav, M. Vashista, and M. Z. K. Yusufzai. 2023. "Impression creep behaviour of different zones of pulsed gas tungsten arc welded Ti-6Al-4V alloy." **Materials Today Communications** 36:106722.
11. P. Kashyap, G. Sainath, **N. Kumar**, and Surya D. Yadav. 2023. "On the Deformation Mechanism and Dislocation Density Evolution in A Polycrystalline Nano Copper at 10 K–700 K/108 s− 1–109 s− 1 Employing Molecular Dynamics Simulations."The International Conference on Metallurgical Engineering and Centenary Celebration.

List of Conferences

1. Poster presentation titled “A dislocation creep model to study the creep deformation behavior in the nickel based disk superalloys” at the **16th International Conference on Creep and Fracture of Engineering Materials and Structures held during 28th July –**

2nd August 2024, organized by Department of Materials Engineering, Indian Institute of Science, Bengaluru.

2. Oral presentation titled "On the Deformation Mechanism and Dislocation Density Evolution in A Polycrystalline Nano Copper at 10 K–700 K/10^{8} s^{-1}–10^{9} s^{-1} Employing Molecular Dynamics Simulations." **Proceedings of the International Conference on Metallurgical Engineering and Centenary Celebration METCENT-2023, 26-28 October, Varanasi, India.**
3. Oral presentation titled "Microstructure Based Flow Stress Modelling of Superalloy 718" at the International Conference on **PROCESSING & MANUFACTURING OF ADVANCED MATERIALS Processing, Fabrication, Properties, Applications was held from July 2 - 7, 2023 Vienna, Austria.**
4. Oral presentation titled "Creep curve modelling of Austenitic Stainless Steel 316LN" at the **76th annual technical meeting of Indian Institute of Metal held at Hyderabad** during 13-16 Nov 2022.
5. Oral presentation titled "Modelling the creep curves of RAFM steel employing a dislocation density reliant model" at **3rd International Conference on Recent Advances in Mechanical Engineering Research and Development (ICRAMERD-2022)** held on August 11 to 13, 2022 and organized by Department of Mechanical Engineering, ITER, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar-751030, Odisha, India.
6. Oral presentation titled titled "Creep curve modelling of Austenitic Steel 316LN" at **2nd International Conference on Materials Science and Engineering (ICMSE-2022) held on June 11-12**, 2022 and organized by the Department of Mechanical Engineering, Dr. B R Ambedkar National Institute of Technology, Jalandhar, Punjab, India
7. Oral presentation titled "Creep curve modelling of Reduced activation ferritic-Martensitic(RAFM) steel" in **CF-8 web conference held during August 24-27, 2021 at Indira Gandhi Centre of Atomic Research, Kalpakkam, Tamilnadu, India.**

PREFACE

Physics based deformation models play a crucial role in the safe life estimation of creep exposed components and for providing insights about hot working processes. Examining the creep and flow response of the metals employing constitutive models pertaining microstructural-based input parameters and variables helps in understanding of deformation characteristics that in turn influence the response of the material during creep and metal forming operations. Modeling and simulation can be a proficient alternative technique that provides the solutions and insights about the various issues. Creep phenomena and metal hot working both involves the movements of dislocations. Therefore, the mechanisms of substructure evolution involve similar physics for both the cases. Since creep research focuses on limiting strain and strain rates at high temperatures, hot working studies aim to at relatively higher strain rates between 10^{-2} and 10^{2}/s. In either creep or hot deformation, the dislocations are the mostly responsible for accommodating plastic deformation. Therefore, while capturing their interactions dislocation density-based models can be developed that provide the anatomy of the induced microstructure with ongoing creep as well as during hot working. In this direction, dislocation density based physical modeling is a decent choice, as it elucidates the complex deformation behaviours as well as provides the insights about the ongoing substructure evolution. The main objective of this research work done in this thesis is to develop microstructure-based creep and flow stress models to reveal the substructure evolution with ongoing deformation. In each of the chapter, an improved model is presented that fills the gap in the literature to some extent.

Chapter 01. Considering the physics-based approaches flow stress models [4, 5, 34, 37, 63] are represented as,

$$\sigma = f(\sigma_0, \rho, \lambda_{mean}) \tag{1.1}$$

where σ_0 refers to the contribution from short range barriers, ρ is the average dislocation density and λ_{mean} being the mean free path of the dislocations. Following issues were observed with respect to flow stress models.

- A physical based model which also incorporates annealing twin density effect and explains the microstructural evolution during plastic deformation of low stacking fault energy material was not found.
- Most of the flow stress models predicts the microstructure evolution along with flow stress response but the velocity of dislocations and influence on recrystallization phenomena was not observed.
- All the experimental curves are fitted with the models, limiting the prediction capabilities.
- Individual contribution of different type of strengthening was rarely addressed.

Similarly, creep rate is modelled as,

$$\dot{\varepsilon} = f\left(\rho_m, \rho_b, \rho_{dip}, R_{sub}, T, \sigma_{appl}, N_v, r_p, D_{cav}, D_{ppt}\right), \tag{1.2}$$

where, ρ_m is mobile dislocation density, ρ_b is boundary dislocation density, ρ_{dip} is dipole dislocation density, R_{sub} is the subgrain radius, N_v is the number density of the precipitate, T is temperature, σ_{app} is applied stress, D_{cav} is the cavitation damage and D_{ppt} is damage due to coarsening of precipitates.

The problem lies in a way that, if models address complete creep curve then microstructural evolution and all other important parameters are not demonstrated [14, 43, 66]. Impact of all

internal variables during the creep exposure is very important and rarely reported. Following issues were observed with existing creep models:

- Slip systems were not incorporated in rate equations of microstructural evolution.
- Influence of stacking fault energy on dislocation velocities was not considered.
- Complex dislocation climb velocity models were used.
- Temperature dependent shear modulus was not incorporated.
- Evolution of some variables was ignored in the literature, that are boundary dislocation spacing, subgrain boundary mobility, dipole capture spacing, climb stress, mean radius of precipitates
- Evolution of damage due to different types of precipitates was not demonstrated separately.
- Temperature and time dependent mobility model for subgrain boundary migration was not implemented.

In light of these issues, physics based flow stress and creep models were developed in the subsequent chapters to address these issues.

Chapter 02. As the flow stress is a crucial parameter in understanding thermomechanical processes such as extrusion, rolling, forging, and other manufacturing processes, its modelling depends on complex microstructures that enable the definition of internal variables. In order to get more insights about the microstructure evolutions during the hot deformation a physical-based model for DDRX that validates the simulation results in terms of flow curves, dislocation density, DDRX fraction, and the predicts the dislocation velocities is a need. In this chapter a flow stress model was developed and validated with the experimental data of IN 718WP.

The key points of this new model is given below,

$$\sigma_{deform} = \underbrace{\sigma_{dis} + \sigma_{HP}}_{athermal\ stress} + \underbrace{\sigma_{ss} + \sigma_{gen}}_{thermal\ stress} \quad (2.1)$$

In Equation (2.1), where σ_{dis}, $\sigma_{HP,}$ and σ_{ss} are the strength contributions due to dislocations, grain size and solid solutions, respectively. σ_{gen} represents strength contribution due to interaction among orthogonal dislocations. The estimation of v_{gl} can be done using the following approach [107],

$$v_{gl} = \lambda_{mean} v_0 exp\left(-\frac{\Delta G}{k_B T}\right) sign(\sigma_{SR_{eff}}) \quad (2.2)$$

In Equation (2.2), λ_{mean} is the mean free path can v_0 is attempt frequency, ΔG is the average activation energy needed to encounter the obstacles, k_B is the Boltzmann constant and $\sigma_{SR_{eff}}$ is the difference between the total flow stress and athermal stress as orthogonal dislocations.The mean free path can be estimated by considering the Pythagorean summation and taking all the possibilities as [113],

$$\frac{C_k}{\lambda_{mean}} = \frac{1}{h_m} + \frac{1}{s} + \frac{1}{g_{avg}} \quad (2.3)$$

Herein, C_k is the dislocation interaction coefficient, s is dislocation substructure size, g_{avg} is the average grain size and h_m is mobile dislocation spacing. The total flow stress ($\sigma_{total,flow}$) response during the hot deformation is estimated using the rule of the mixture of non-recrystallized and recrystallized areas as [116],

$$\sigma_{total,flow} = (1 - X_{DDRX})\sigma_{deform} + X_{DDRX}\sigma_{DDRX} \quad (2.4)$$

Where X_{DDRX} is recrystallization fraction, σ_{DDRX} is the flow stress contribution from DDRX region and σ_{deform} is the flow stress response from unrecrytallized region. The dislocation density-reliant flow stress model was developed by considering the physics behind DDRX phenomena to address the complete flow stress curve as well as microstructure evolution for the

IN718WP superalloy. Model capabilities for microstructure prediction was validated by comparing the results obtained with EBSD data in terms of dislocation density and DDRX fraction. The important conclusions of this work are,

- Model predicts the flow stress response with a single set of calibrated parameters for the wide range of temperature and strain rate.
- The average grain size was observed to be decreasing and approaching to steady state easily at low strain rates or higher temperatures as compared to that of higher strain rates or lower temperatures.

Chapter 03. In this chapter a flow stress model was developed that includes the addition of twin boundaries as a strengthening elements as a new addition to previous developed models [34]. The model was validated with respect to flow curves of IN718 [4]. Total flow stress response can be expressed as,

$$\sigma_{flow} = \sigma_{dis} + \sigma_{HP} + \sigma_{ss} \, , \tag{3.1}$$

Herein, the strengthening contribution from the dislocation is given by Taylor hardening relations,

$$\sigma_{dis} = \alpha M G_{sm} b \sqrt{\rho_i} \, , \tag{3.2}$$

Herein, α is a parameter that is dependent on the dislocation interactions, ρ_i is immobile dislocation density, M is the Taylor factor, b is magnitude of Burgers vector and G_{sm} is shear modulus. Furthermore, by incorporating the twin boundary concept [137], the grain boundary strengthening contribution is calculated using the modified Hall-Petch contribution and is represented as [34],

$$\sigma_{HP} = \frac{K_{HP} G_{sm}(T)}{\sqrt{g_{eff}} G_{RT}} = \frac{K_{HP} \; G_{sm}(T)}{\sqrt{g} G_{RT}} \left[1 + 2K_t ln\left(\frac{g}{g_0}\right)\right]^{\frac{1}{2}} . \tag{3.3}$$

Herein K_{HP} is the Hall-Petch strengthening coefficient, $G_{sm}(T)$ is temperature dependent G_{sm}, G_{RT} is room temperature G_{sm} and K_t is a constant, g is the grain size before annealing and g_0 is the grain size after annealing. The short range contribution provided by the solid solutions is estimated through the following expression [138],

$$\sigma_{ss} = \left[\sum_{i=0}^{n} Z_L G(T)^{\frac{3}{2}} \left(\alpha_s \delta_i + \acute{\eta}(T)\right)^2 c_i\right]^{\frac{2}{3}} \quad , \tag{3.4}$$

Herein Z_L is a material parameter, c_i is solute concentration α_s is a dimensionless constant and $\acute{\eta}(T)$ is the temperature-dependent misfit of G_{sm}. The major outputs of the model are discussed below,

- The contributions of dislocation strengthening and Hall-Petch strengthening dominates over others with respect to the overall σ_{flow}.
- The predictions of flow responses are not good and there is significant deviation in experimental and predicted flow curves if twins are not considered and the traditional Hall-Petch equation is used.

Chapter 04. The anatomy of the induced microstructure with ongoing creep plays a crucial role in the safe life estimation of components and for the new alloys development programs. In this chapter a creep model was developed and validated with the experimental data of RAFM steel. The novelty of the model lies with [47, 57]:

- Implementation of temperature and time dependent mobility model for subgrain boundary migration as,

$$M_{sb} = \underbrace{\frac{2\pi\eta D_s \Omega}{bk_B T}}_{\text{Core mobility}} + \underbrace{\frac{2\pi b D_{vp} \Omega}{h_b^2 k_B T}}_{\text{Lattice diffusion mobility}} \quad (4.1)$$

Herein, η is the transfer coefficient of dislocation core to jogs and h_b is boundary dislocation spacing, D_{vp} is pipe diffusion coefficient and D_s is the lattice self-diffusion coefficient.

- A more simplified method is presented to evaluate the climb velocity and associated equations are presented in form of variables N_1, N_2 and N_3 to obtain the climb stress and climb velocity.

Equation for the dislocation climb velocity can be given as,

$$v_{cl} = \frac{D_s \Omega \sigma_c}{bk_B T} \quad (4.2)$$

Combined equation for climb velocity and climb stress can be given as,

$$\sigma_{cl} + \frac{v_{cl}}{B_{vis}} = \frac{G_T b}{2\pi(1-\upsilon)} \frac{2}{d_{spon} + d_{dip}} \quad (4.3)$$

$$\sigma_{cl} - v_{\mathrm{cl}} * N_1 = 0, where\ N_1 = \frac{bk_B T}{D_s \Omega} \quad (4.4)$$

$$\sigma_{cl} + v_{cl} * N_2 = N_3, where\ N_2 = \frac{1}{B_{vis}}, N_3 = \frac{G_T b}{2\pi(1-\upsilon)} \frac{2}{d_{spon} + d_{dip}} \quad (4.5)$$

$$\sigma_{cl} = \frac{N_3 * N_1}{(N_2 + N_1)} \quad (4.6)$$

- Temperature-dependent shear modulus is incorporated.
- Evolution of additional variables that were not discussed in the literature, those are boundary dislocation spacing, subgrain boundary mobility, dipole capture spacing, climb stress, mean radius of MX (V and Ta based carbonitrides) precipitates, mean radius of $M_{23}C_6$ carbides is presented and discussed thoroughly.
- Evolution of damage due to two different types of precipitates is demonstrated separately.

The following observation can be noted from the investigated conditions:

- Mobile and dipole dislocation density decrease with ongoing creep due to glide and climb recovery. In the beginning of creep exposure, boundary dislocation density is found to be increasing and afterward decreases due to dominance of subgrain growth.
- Radius of subgrain is found to coarsen with ongoing creep. The both dislocation velocities were found to be increasing with creep.
- The computed internal stress was observed to be decreasing with creep. The effective stress on dislocations was observed to be increasing with creep.

Chapter 05. Existing models LSFE materials either do not provide information about the microstructural changes occurring during creep or employ too many adjustable parameters. Thus, a sound model that considers the influence of SFE on dislocation velocities, explains the evolution of the internal variable along with creep curves, and works with a single set of calibration parameters is a need. In this chapter a creep model was developed and validated with the experimental data of IN718. The new equations that were implemented in this work are,

- Glide velocity*:*

$$v_{gl} = a_1 M\Gamma \left(\frac{1}{br_p}\right) v_{p,i} L_p C_j D_s \, sinh\left(\frac{\sigma_{effe} b^2 L_p}{M k_B T}\right), \quad (5.1)$$

In Equation (5.1), $v_{p,i}$ is the phase fraction of the precipitates, a_1 is a prefactor for the gliding velocity, Γ is the stacking fault factor, X is the magnitude of the SFE, L_p is the mean spacing between all types of precipitates, σ_{effe} is effective stress and C_j is the jog density.

- Climb velocity

$$v_{cl} = \frac{\Omega D_{vp} \sigma_{cl}}{b K_B T} . \Gamma, \quad (5.2)$$

- Rate equation of dislocation densities incorporated slip system information, for example,

$$\dot{\rho}_m = \overbrace{\underbrace{\left(\frac{v_{gl}}{\lambda_{mean}}\rho_m\right)}_{production}}^{\rho_m^+} - \overbrace{\underbrace{\left(\frac{v_{gl}}{s}\rho_m\right)\left(1-\frac{1}{n_{slip}}\right)}_{immoblization} - \underbrace{d_{spon}\rho_m v_{gl}(\rho_m+\rho_i)\left(\frac{1}{n_{slip}}\right)}_{glide\ recovery}}^{\rho_m^-}, \quad (5.3)$$

In Equation (5.3) ρ_i is immobile dislocation density, d_{spon} is the spontaneous annihilation distance, n_{slip} is the number of active glide systems and $s = k_c/(\rho_{imob})^{0.5}$ is the dislocation substructure size, where k_c is the calibration parameter. Herein, we assumed that the total number of active glide systems is $n_{slip,}$ and an equal number of dislocations are available on each system. The normalisation will be $1/n_{slip}$, for any dislocation reaction. Furthermore, since the reaction partners are available on all glide systems, we replaced $1/n_{slip}$ with $(n_{slip}-1)/n_{slip}$ [113].

Experimental creep curves were modelled and validated up to the secondary stage. In addition to this, the model was shown to be capable of addressing the evolution of the internal variables such as ρ_m, ρ_i, λ_{mean}, v_{gl}, σ_{int}, σ_{effe} and σ_{cl} with creep time. To get more confidence about the model predictions, the boundary dislocation density estimated from the EBSD characterization was compared with the dislocation density predicted by the model. From the explored conditions following conclusions can be drawn,

- The model suggests that both the dislocation densities, internal stress and climb stress increase over the period of creep. Whereas the mean free path, glide velocity and effective stress have a decreasing trend.
- The proposed model is capable of addressing the effect of the stress and temperature on the primary to steady state creep regime using a single set of parameters.

Chapter 06. In this chapter a creep model was developed and validated with the experimental data of steel 316 LN.

This work presents some improvements compared to existing literature in the sense that,

- A more generalized mobility model is assimilated that considers temperature dependent maximum back stress.

$$M_{cg} = \frac{D_0 b}{k_B T}\, e^{\frac{\sigma_{eff} b^3}{k_B T}}\, e^{-\frac{Q}{RT}\left[1-\left(\frac{\sigma_{eff}}{\sigma_{max}}\right)^2\right]}. \quad (6.1)$$

where, σ_{max} = 1.5×σ_{UTS}, and Q being the activation energy for self-diffusion.

In order to make the equation (6.1) more physical, temperature dependent ultimate tensile strength is incorporated to find the maximum back stress as σ_{max} = 1.5×$\sigma_{UTS\,(T)}$

$$\sigma_{UTS\,(T)} = -1.1241\,T + 1411.8000 \quad (6.2)$$

- Effective stress was considered in place of applied stress for estimating dislocation glide velocity

$$v_{cl} = M_{cg} b \sigma_{effe}\,, \quad (6.3)$$

- The temperature dependent shear modulus is incorporated

Outcome of this work is delineated in brief as,

- Mobile and forest dislocation density increase and average dislocation glide distance decreases with ongoing creep. The Internal stress is found to be increasing whereas the effective stress decreasing with ongoing creep.
- The velocity and mobility of dislocations decrease with accumulated strain. They were observed between 2.37 ×10^{-12} - 1.45 ×10^{-11} m/s and 1.61 ×10^{-10} - 3.41 ×10^{-10} $mPa^{-1}s^{-1}$, respectively.
- The damage caused by the carbonitrides precipitate (MX-type) and carbides precipitate ($M_{23}C_6$-type) are increasing with ongoing creep. Cavitation damage rate was found to be increasing with creep time.

References section provides the list of relevant references (258) cited in Chapter 1-6 of the thesis.