Chapter 07

7.1. Summary and conclusions

The dislocation density reliant mean field deformation models were developed for addressing the flow curves of IN718WP and IN718 and creep curves of RAFM Steel, IN718 and 316 LN steel. Developed models were validated with experimentally obtained flow curves and creep curves. Furthermore, the model predictions were corroborated with the results obtained by the characterization techniques such as LOM, SEM, EBSD and TEM. This approach enabled us to understand the microstructure evolution during each time step of the deformation. Hence, this approach is not only for merely curve fitting; rather, microstructure-reliant parameters can be tracked at every single time step. Chapter wise major conclusions of this work are given below,

In Chapter 2, A dislocation density-based flow stress model was developed by considering the physics behind DDRX phenomena to address the complete flow stress curve and microstructure evolution for the IN718WP superalloy. The model predicted the evolution of critical internal variables such as ρ_m and ρ_i and DDRX fraction with ongoing deformation. The model also demonstrates the evolution of dislocation velocities such as v_{gl} and v_{cl} in each time step of deformation. The effect of the strain rate and temperature on the flow stress curves was delineated employing model prediction and experimental data. Model capabilities for microstructure prediction were validated by comparing the results obtained with EBSD data regarding dislocation density and DDRX fraction. Model predicts the flow stress response with a single set of parameters for the wide range of temperature and strain rates. The important findings are given below,

- Recrystallized volume fraction was observed to be high at low strain rate or high temperature, observed through EBSD measurements and model predictions. The average grain size decreased and approached to steady state quickly at low strain rates or higher temperatures compared to higher strain rates or lower temperatures.
- The mobile dislocation density increased with increasing the strain at a constant temperature/strain rate. ρ_m has lesser magnitude at higher temperature / lower strain rate due to dominance of softening
- Model output suggests that the higher climb and glide velocity of dislocations promoted the occurrence of recrystallization phenomena.
- Presented model is practically useful for analyzing experimental flow stress response, as the single set of parameters can be determined through fitting of only few experimental flow curves. Rest of the curves can be modeled through the obtained single set of parameters.

In Chapter 3, Flow stress response of IN 718 was modelled using a physics-reliant flow stress model. Both the LR and SR strengthening contributions were considered for predicting the overall flow behavior. The important findings are given below,

- Contributions of dislocation strengthening and Hall-Petch strengthening dominates over others with respect to the overall σ_{flow}.
- Predicted flow stress response is found to have reasonable agreement with experimental. 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 traditional Hall-Petch equation is used.

In Chapter 4, Creep curves of RAFM steel were simulated employing an improved creep model. The model has ability to address the creep curves of RAFM steel, for up to the onset of the tertiary regime. The advantage of the current approach is, it can predict the evolution of dislocation densities (mobile, dipole, and boundary), subgrain radius, dislocation glide velocity, climb velocity, internal stress, climb stress, effective stress, subgrain size, boundary pressure, boundary dislocation spacing, subgrain mobility, dipole capture spacing, softening due to precipitate and cavitation with ongoing creep. It is also possible to capture the change in each parameter with respect to each time step of the creep. The modeled creep curves are found to have a reasonable agreement with the experimental creep curves. Furthermore, other model outputs that are dislocation densities, precipitate and subgrain size are corroborated with the experimental data available in the literature [10, 49, 58, 159, 161-163, 173]. The important findings are given below,

- Mobile and dipole dislocation density decreases with ongoing creep due to glide and climb recovery. At the beginning of creep exposure, boundary dislocation density is found to be increasing and afterwards decreases due to the dominance of subgrain growth
- The radius of subgrains was predicted to increase with ongoing creep. Both dislocation velocities were found to be increasing with creep.
- The computed internal stress was decreasing with creep. The effective stress was observed to be increasing with creep. On the other hand, subgrain boundary pressure follows the trend of boundary dislocation density.
- Predicted boundary dislocation spacing decreases and subgrain boundary mobility increases with creep.
- Predicted climb stress increases and dipole capture spacing decreases with creep.

In Chapter 5, A microstructure-based creep model has been developed and applied to understand the creep performance of the Inconel®718 superalloy. The creep tests were conducted and 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.

In Chapter 6, A hybrid creep model was developed with the capability to address the creep behaviour of 316 LN steel. Model can deliver creep curves and microstructure evolution together in each time step of deformation. Evolution of variables that are dislocation densities, average dislocation glide distance, mobility and velocity of dislocations, coarsening of precipitates and respective damage, and damage due to cavitation during creep can be obtained. The important findings are given below,

- The mobile dislocations act as quick response internal variable thus saturates at relatively shorter creep time. The forest dislocations are produced once the mobile dislocations get forested. Therefore, forest dislocations attain metastable configuration with slow rate, therefore, it takes relatively more time to achieve the saturation values.

- ρ_m and ρ_f 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.
- The damage rate caused by the carbonitrides precipitate (MX-type) and carbides precipitate ($M_{23}C_6$-type) are increasing with ongoing creep. Cavitation damage rate was also increasing with ongoing creep.
- During creep, as more dislocations are produced at higher stresses, the possibility of dislocation pile-ups at coarse precipitates near grain boundaries also increases, which in turn promotes the formation of creep cavities and early failure of specimens exposed to higher stresses.

7.2. Outlook

- The developed mean-field creep models can be improved by considering the exact shape of the precipitates.
- DRX with strain induced nucleation model may be incorporated in the rate equations for the better predictions at higher creeping conditions.
- The flow stress model can be further improved and extended to particle strengthened materials by incorporating the effect of the second phase particle on the recrystallization.
- All the developed models can be combined with crystal plasticity framework for the better and more realistic predictions.