CHAPTER 7

SUMMARY AND SCOPE FOR FUTURE WORK
Summary and scope for future work

The studies pertaining to the effect of multiaxial state of stress, introduced by incorporating circumferential U-notches of various notch radii on cylindrical specimens, on creep rupture behaviour of 2.25Cr-1Mo, 9Cr-1Mo and modified 9Cr-1Mo steels have been summarized:

7.1 Summary

The rupture life of all the steels in presence of notch was found to be higher than those of plain specimens, exhibiting notch strengthening behaviour. The strengthening of the steels in presence of notch was found to be in the increasing order of 2.25Cr-1Mo steel, 9Cr-1Mo steel and modified 9Cr-1Mo steel. Ductility of the steels decreased in presence of notch. Fractographic studies revealed typical cup and cone transgranular ductile fracture for all the steels at relatively higher stresses. The evidence of creep cavitation induced brittle fracture at relatively lower applied stresses was observed.

The rupture life of the steels was found to increase with notch sharpness (notch acuity ratio) and tends to saturate at relatively higher notch acuity ratio. The extent of strengthening with notch acuity ratio was found to depend on the material. It was in the increasing order of 2.25Cr-1Mo, 9C-1Mo and modified 9Cr-1Mo steel. Creep rupture ductility of the steels decreased significantly with increase in notch acuity ratio and tends to saturate at higher notch acuity ratio. The increase in notch sharpness decreased the creep rupture ductility to a greater extent in modified 9Cr-1Mo steel and least in 9Cr-1Mo steel.
Significant variation in creep fracture appearance was observed depending on the material and notch sharpness. Shear-lip type of failure of the notched specimen was observed for notches of relatively lower notch acuity ratio $< 4$ whereas, for notch acuity ratio $\geq 4$, intergranular creep cavitation close to notch root and the ductile dimple fracture around the central region of notch throat plane were observed. Under multiaxial state of stress, 2.25Cr-1Mo was found to be more susceptible to creep cavitation and 9Cr-1Mo steel the least.

The FE analysis revealed the presence of multiaxial state of stress across the notch. With creep exposure, the stress distribution changed progressively to attain a stationary state. The von-Mises stress was found to remain below the net applied stress resulting in notch strengthening in the steels. The decrease in von-Mises stress with increase in notch sharpness led to higher strengthening. The saturating tendency of von-Mises stress with increase in notch acuity ratio resulted in saturation of notch strengthening. The faster stress relaxation of von-Mises stress for modified 9Cr-1Mo steel resulted in higher extent of notch strengthening than those in 2.25Cr-1Mo and 9Cr-1Mo steels.

The variation in maximum principal stress across the notch throat plane showed a maxima having value more than the net applied stress. The maxima in principal stress increased with notch acuity ratio and its position progressively shifted towards the notch root region. For the relatively shallow notches (notch acuity ratio $< 4$), the presence of relatively high and uniform von-Mises stress across notch throat plane induced uniform cavity nucleation across the notch throat plane. Presence of high maximum principal and hydrostatic stresses at the central region of notch throat plane caused preferential growth of the nucleated cavities, resulting in dimple ductile appearance, as observed experimentally.
For relatively sharper notches (notch acuity ratio $\geq 4$) maximum von-Mises stress at the notch root region led to nucleation of creep cavities. High principal stress along with high hydrostatic stress resulted in growth of the nucleated cavities at the near notch root region. Coalescence of the creep cavities would have led to the propagation of crack from the notch root region towards the central region of the notch throat plane, as observed experimentally.

Prediction of creep rupture behaviour of the steels under multiaxial state of stress was carried out based on representative stress concept. The relative contribution of maximum principal stress, hydrostatic stress and von-Mises stress to the representative stress in governing the creep rupture life under multiaxial state of stress was assessed. The stresses estimated at skeletal point were implemented to estimate the representative stress. The model proposed by Cane, which considers the inter-relationship between creep deformation and cavitation, represented the experimental multiaxial creep data well for the steels. The von-Mises stress was found to predominantly govern creep rupture life of the steels under multiaxial state of stress.

The multiaxial creep rupture behaviour of the steels was also predicted based on the FE analysis coupled with continuum damage mechanics (CDM). The creep deformation and damage laws were incorporated in FE analysis using VUMAT subroutine for calculating the stresses, creep strains and damage in the plain and notched specimens. The VUMAT subroutine was first implemented for prediction of creep strains and rupture lives of the steels under uniaxial state of stress before applying it to multiaxial state of stress. The predicted creep strains and rupture life was found to be in good agreement with the experimental data, which validated the procedure adopted in the subroutine for FE analysis considering CDM. The estimated creep damage evolution of the steel under multiaxial state of stress could predict the
observed variations in fracture behaviour of the steels. The assessment predicted the higher rate of creep damage accumulation in 2.25Cr-1Mo steel than in 9Cr-steels. Experimentally observed higher propensity to creep cavitation in 2.25Cr-1Mo steel than in 9Cr-steels under multiaxial state of stress has been validated. The rupture life of the steels under multiaxial state of stress predicted based on the continuum damage mechanics coupled with FE analysis was found to be in good agreement with the experiments within a factor of 3.

7.2 Suggestions for future work

Based on the study of effect of multiaxial state of stress on creep behaviour of 2.25Cr-1Mo, 9Cr-1Mo and modified 9Cr-1Mo steels, following suggestions have been made for further investigation

1. Creep deformation and rupture behaviour of materials subjected to sharper notches as encountered in fabricated component may be carried out to establish the multiaxial state of behaviour of component.

2. Response of material to multiaxiality, incorporated by other means like bi-axial and torsion etc., can be assessed and compared for realistic prediction of creep deformation, damage and rupture.

3. The prediction of creep rupture life under multiaxial state of stress can be validated by performing component testing.

4. Multiaxial creep response of material can be utilized for predicting type IV cracking behaviour of ferritic steel weld joints which are subjected to multiaxial stress due to microstructural inhomogeneity.

5. Long term creep tests can be performed to assess the notch strengthening / weakening behaviour of these steels.
6. Studies can also be extended to dynamic loading condition to assess creep-fatigue interaction under multiaxial state of stress.

7. The studies can be extended to diverse materials having different deformation characteristics.