SYNOPSIS

Structural components operating in the creep regime are subjected to multiaxial state of stress which arises due to change in geometry, microstructural inhomogeneity as in weld joint and also due to the mode of loading during service. The components are generally designed based on uniaxial creep data. For realistically assessment of life of such components, it is important to evaluate and predict the creep rupture life under multiaxial state of stress which influences the creep deformation and rupture behaviour appreciably. The effect of multiaxial state of stress on creep deformation and rupture behaviour of materials is generally studied by the introduction of notch in cylindrical specimens.

Creep rupture behaviour of 2.25Cr-1Mo, 9Cr-1Mo and modified 9Cr-1Mo ferritic steels under multiaxial state of stress have been assessed and compared in this investigation. Multiaxial state of stress was incorporated in cylindrical specimen of the steels by introducing circumferentially U-notch with various notch root radius keeping the minimum diameter of the specimen constant (5 mm) similar to plain specimen and shoulder diameter of 8.35 mm. Notches of different root radii of 5 mm, 2.5 mm, 1.25 mm, 0.83 mm, 0.5 mm and 0.25 mm were used to vary the multiaxial state of stress. These notch configurations led to the variation in notch acuity ratio (ratio of notch plane diameter to notch root radius) from 1 to 20 and stress concentration factor of 1 to 3.4. Creep tests have been carried out at net applied stresses ranging from 90 - 230 MPa and at 873 K on the plain and circumferentially U-notched specimens of the steels. Scanning electron microscopy investigation was carried out to assess the effect of notch sharpness on creep fracture appearance and damage accumulation in the steels.
The creep deformation of the ferritic steels under uniaxial stress was characterized by a small instantaneous strain on loading, a transient primary stage, a secondary stage followed by relatively prolonged tertiary creep regime. The variation of steady state creep rate \( (\dot{\varepsilon}_c) \) with applied stress \( (\sigma) \) for all the three ferritic steels followed Norton’s law, a power law relation of the form, \( \dot{\varepsilon}_c = A\sigma^n \). The 2.25Cr-1Mo steel was found to have lowest creep deformation resistance and modified 9Cr-1Mo steel exhibited highest creep deformation resistance among the steels. The stress exponent ‘\( n \)’ value was 6.02 for 2.25Cr-1Mo steel, 8.24 for 9Cr-1Mo steel and 12.92 for modified 9Cr-1Mo steel. The modified 9Cr-1Mo steel possessed higher creep rupture life than both the 2.25Cr-1Mo and 9Cr-1Mo steels. The 9Cr-1Mo and 2.25Cr-1Mo steels exhibited comparable creep rupture life over the investigated stress range.

All the steels failed in the ductile dimple appearance. The estimated damage tolerance factor of more than 4 revealed that in all the steels microstructural degradation was the main creep damage mechanism in the steels. The 2.25Cr-1Mo was found to be more prone to creep damage than the 9Cr-steels.

The rupture life of all the steels increased in presence of notch. The creep 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 carried out on 2.25Cr-1Mo steel exhibited typical cup and cone transgranular ductile fracture at relatively higher stresses. Width of the shear lip zone was found to decrease with decrease in applied stress. The evidence of creep cavitation induced brittle fracture at relatively lower applied stresses was observed. In 9Cr-1Mo steel, the fracture appearance in presence of notch as in plain specimen was predominantly transgranular ductile at all the stresses investigated.
Effect of degree of multiaxial state of stress on creep behaviour has been assessed by carrying out creep tests on specimens having different notch radius. The rupture life increased with notch sharpness (notch acuity ratio) for all the steels. The notch strengthening was found to saturate at relatively higher notch acuity ratio. The extent of strengthening with notch acuity ratio was found to depend on the material’s deformation characteristics. It was in the increasing order of 2.25Cr-1Mo, 9C-1Mo and modified 9Cr-1Mo steel. With increase in notch acuity ratio, the strengthening increased more rapidly in modified 9Cr-1Mo steel than that in 2.25Cr-1Mo and 9Cr-1Mo steels. The increase in strengthening with notch acuity ratio was comparable for 2.25Cr-1Mo and 9Cr-1Mo steels. Creep rupture ductility of the steels decreased significantly with increase in notch acuity ratio and tends to saturate at higher notch acuity ratio. The 9Cr-1Mo steel exhibited relatively higher ductility than the 2.25Cr-1Mo steel whereas the modified 9Cr-1Mo the least. 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.

Creep fracture appearance was found to vary significantly with the notch sharpness (notch acuity ratio). Shear-lip type of failure of the notched specimen was observed for notches of relatively lower notch acuity ratio < 4, as in plain specimen. Shear-lip, characteristic of cup and cone type of failure was caused by final mechanical instability around the notch root region. This suggests that the failure initiated at the central region of the notch throat plane by plasticity-induced intragranular ductile dimple failure mode and propagated towards the notch root. For relatively sharper notches of notch acuity ratio ≥ 4, quite appreciable change in fracture appearance was observed. Intergranular creep cavitation close to notch root and the ductile dimple fracture around the central region of notch throat plane were
observed for relatively sharper notches at relatively lower net applied stresses. These evidences clearly indicate that creep cavitation would have started from the notch root region and propagated towards the central region leading to ductile dimple failure by plastic instability at the central region. The fracture appearance changed from predominantly dimple ductile appearance to predominantly intergranular creep cavitation appearance with increase in notch acuity ratio and decrease in net applied stress. The fracture appearance in 9Cr-1Mo showed relatively more ductile dimple appearance for a given net applied stress and notch acuity ratio than that in 2.25Cr-1Mo steel and this has been reflected in higher creep rupture ductility of the 9Cr-1Mo steel than in the 2.25Cr-1Mo steel. Fracture appearance in modified 9Cr-1Mo steel was similar to those in 2.25Cr-1Mo and 9Cr-1Mo steels but the prevalence of intergranular creep cavitation was more for a given applied stress and notch acuity ratio. Metallographic evidences have substantiated the changes in failure mode with notch acuity ratio.

The experimentally observed notch strengthening and its extent, and the difference in fracture appearance of the steels have been explained on the basis of the finite element (FE) analysis of stress distribution across the notch. Due to geometrical and loading symmetry, 2D axisymmetric analysis was carried out using quadrilateral elements. FE analysis was performed incorporating elasto-plastic-creep behaviour of the steels. The plastic deformation of the steels was considered to be governed by Hollomon equation \( \sigma_t = K(\varepsilon_p)\) whereas creep deformation by Norton’s law \( (\dot{\varepsilon}_c = A\sigma^n)\). The FE analysis revealed that the multiaxial state of stress was generated in presence of notch in cylindrical specimen of the steels subjected to uniaxial stress due to the imposed constraint. Stresses were found to vary significantly across the notch. As creep deformation progresses, the regions of high stress shed its load to the
regions of lower stresses. Stresses distribution across the notch was found to change with creep exposure and approached to a stationary state.

Creep rupture life of the material under multiaxial state of stress depends on the components of stresses viz., maximum principal stress, hydrostatic stress and von-Mises stress in governing the creep deformation and cavitation. The von-Mises stress governs the creep deformation and cavity nucleation processes whereas the maximum principal and hydrostatic stresses control the cavity growth. The von-Mises stress was found to remain below the net applied stress and increased towards notch root. The maximum principal stress was found to be lower than the net applied stress at the central and notch root regions and showed a maximum value which was more than the net applied stress. The behaviour of hydrostatic stress under stationary state condition across the notch throat plane was similar to that of principal stress but the maximum value of the hydrostatic stress remained below the net stress. The decrease in von-Mises stress below the net applied stress after stress redistribution led to the notch strengthening in the steels.

Notch strengthening was found to be comparable for 2.25Cr-1Mo and 9Cr-1Mo steel. However, modified 9Cr-1Mo steel exhibited greater extent of notch strengthening. The von-Mises stress relaxed with creep exposure at different rates and to a different extent depending upon the steels. The relaxation was relatively faster for modified 9Cr-1Mo steel and slowest for 2.25Cr-1Mo steel, because of higher stress sensitivity of creep deformation in modified 9Cr-1Mo steel than that in 2.25Cr-1Mo and 9Cr-1Mo steels. The normalized (with respect to the respective yield stress) von-Mises stress was found to be in the increasing order of modified 9Cr-1Mo, 9Cr-1Mo and 2.25Cr-1Mo steel. Higher von-Mises stress across the notch throat plane in 2.25Cr-1Mo steel was resulted due to the relatively less extent of stress relaxation.
than in the other two steels. This implies that at a given net applied stress, 2.25Cr-1Mo steel would spend most of its life time at higher von-Mises stress than in modified 9Cr-1Mo steel, resulting in lower notch strengthening, as observed experimentally.

FE analysis was extended to study the effect of notch sharpness on the stress distribution across the notch throat plane to assess its influence on creep rupture life of the steels. The von-Mises across the notch throat plane was found to decrease with increase in notch acuity ratio. The variation in von-Mises stress across the notch throat plane was not found to change appreciably for relatively shallow notches (notch acuity ratio < 4). However, in relatively sharp notches (notch acuity ratios ≥ 4), the von-Mises stress increased gradually at the notch root region, however remained below the net stress for all the notch acuity ratios investigated. The variation in maximum principal stress across the notch throat plane showed a maxima and it had value more than the net applied stress for all notch acuity ratios. The maxima in principal stress increased with notch acuity ratio and its position progressively shifted towards the notch root region. Similar variation in hydrostatic stress across the notch throat plane for different notch acuity ratios was observed; however, the maximum value of hydrostatic stress remained below the net stress for all the notch acuity ratios investigated. The decrease in von-Mises stress with increase in notch acuity ratio led to higher notch strengthening. The saturating tendency of von-Mises stress with increase in notch acuity ratio would have been the cause for saturation of notch strengthening at higher notch acuity ratio. The von-Mises stress decreases significantly with increase in notch acuity ratio for all the steels. Larger extent of decrease in von-Mises stress with notch acuity ratio in all the steels increased the notch strengthening to greater extent. The stress was found to relax with creep
exposure at different rate and to a different extent depending upon the material and notch sharpness (notch acuity ratio). The stress relaxation was relatively faster for modified 9Cr-1Mo steel especially for sharper notches and slowest for 2.25Cr-1Mo steel. This resulted in higher extent of notch strengthening in modified 9Cr-1Mo steel than those in 2.25Cr-1Mo and 9Cr-1Mo steels.

The observed variations in fracture appearance in the steels with notch sharpness have been explained based on the FE analysis of stress distribution across the notch throat plane. For the relatively shallow notches (notch acuity ratio < 4), the presence of relatively high and uniform von-Mises stress across notch throat plane has been expected to produce more or less uniform cavity nucleation across the notch throat plane. Growth of the nucleated cavity is influenced by the multiaxial state of stress. The hydrostatic stress plays a significant role in cavity growth under constrained conditions. Presence of high hydrostatic stress at the central region of notch throat plane would have caused preferential growth of the nucleated cavities. Thus, even though nucleation of cavities occurred throughout the notch throat plane of shallow notch, the cavities at the central region of notch throat plane would have grown faster. At some critical strain, plastic deformation becomes localized at the ligament between the cavities causing them to rupture by mechanical instability. This result in cavities coalescence and fracture follows. This mechanism becomes important under high strain-rate conditions as in the shallow notch, where significant strain is realized.

For relatively sharper notches (notch acuity ratio ≥ 4), von-Mises stress at the notch root region was found to be maximum. As the nucleation of creep cavities is controlled by von-Mises stress through plastic deformation, nucleation of creep cavities is expected to be more in the notch root region. High principal stress along
with high hydrostatic stress would have led to the growth of the nucleated cavities at the near notch root region. The cavity growth by principal stress occurs by diffusive transfer of material from cavity surface to the grain boundary. The fracture surface appearance is expected to be intergranular as observed experimentally. 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. Final failure of the ligament at the central region of notch throat plane would have occurred due to mechanical instability, resulting in ductile dimple fracture appearance, as observed experimentally.

For component operating under multiaxial state of stress in creep condition, it is important to predict its creep rupture life. FE analysis was used to predict the rupture life of steels subjected to multiaxial state of stress by estimating the representative stress. The representative stress has been defined as the stress applied to the uniaxial plain specimen, which would result in the same creep rupture life as that of notched specimen. 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 has been assessed considering the available models in open literature. Since the stresses vary significantly across the notch during creep exposure, it is difficult to identify the location in notch throat plane at which the stresses should be considered in defining the representative stress for creep rupture life prediction. FE analysis revealed that there exist a point in the notch throat plane, called as skeletal point, at which the variation of stress across the notch throat plane for different stress exponent ‘n’ in Norton’s law, intersects. The stresses estimated at this point were implemented to estimate the representative stress for predicting the creep rupture life of the steels under multiaxial state of stress.
model proposed by Cane, which has considered 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 the creep rupture life of the steels under multiaxial state of stress.

Detailed FE analysis has also been carried out incorporating continuum damage mechanics (CDM) to predict the damage evolution and creep rupture life of the steels under multiaxial state of stress and to validate the experimentally observed variations in fractography. The creep damage law was incorporated in FE analysis using VUMAT subroutine. The user subroutine was written in FORTRAN and implemented in the ABAQUS FE solver for calculating the stresses, creep strains and damage in the plain and notched specimens. VSPRINC utility subroutine was used for calculating the maximum principal stress at each integration point which was used for estimating representative stress along with von-Mises stress. The creep strain and damage rate equations were solved and increment of these variables was calculated. The variables were updated at the end of increment and passed on to main program. The program was terminated on the attainment of damage to the limit of 0.5. As the damage parameter increased beyond this value, the accelerated creep rate led to severe distortion of the elements. 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 damage evolution in the notched specimens with creep exposure was assessed based on FE analysis coupled with CDM. The damage was found to initiate at the notch root region due to the higher stresses developed as a result of stress
concentration for shallow notches. However, the stress relaxation resulted in shifting of damage towards the centre of notch. Finally, the critical damage ($\omega = 0.5$) reaches at the centre of notch resulting cup and cone type fracture as observed experimentally for shallow notches. Quite different accumulation of creep damage behaviour in relatively sharper notches was observed. The stress redistribution across the notch throat plane led to the higher stresses at the notch root region for relatively sharper notches. Unlike in shallow notches, in sharper notches the damage continues to accumulate at the notch root region and attained the critical value. The crack propagated from the notch root region towards centre resulting in fracture appearance as observed experimentally for sharper notches.

The creep damage accumulation was significantly high for 2.25Cr-1Mo than those in 9Cr-steels. The extent was in the decreasing order of 2.25Cr-1Mo, 9Cr-1Mo and modified 9Cr-1Mo steel. This could be attributed to the higher creep deformation resistance observed in modified 9Cr-1Mo steel than that in 2.25Cr-1Mo and 9Cr-1Mo steels. Experimentally observed higher propensity to creep cavitation in 2.25Cr-1Mo steel than in 9Cr-1Mo steel clearly substantiated the FE-CDM analysis of creep damage evolution in the steels. Observed higher tendency to creep cavitation in modified 9Cr-1Mo steel than that in 9Cr-1Mo steel might be due to its enhanced rupture life, which would have facilitated the nucleated creep cavities to grow leading to intergranular creep cavitation.

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.