INTRODUCTION

Structural components operating at relatively high temperatures are subjected to creep deformation and damage. Multiaxial state of stress arises in such components as a result of change in geometry, inhomogeneous microstructure as in weld joint and also due to the mode of loading during service. The design of components is generally based on uniaxial creep data; however, it is more appropriate to use creep data under multiaxial state of stress. Notched specimens are widely used to study the effect of multiaxial state of stress on creep deformation and rupture behaviour of materials. The presence of notches may exhibit notch strengthening or weakening depending on the notch geometry, testing conditions and deformation characteristics of the material. Notch strengthening is expected when the high axial stresses across the notch throat plane redistributes quickly during creep exposure and decreases below the applied stress. This kind of behaviour is typically observed in relatively ductile materials. However, the notch weakening is expected in situations where the very high axial stress due to the presence of notch redistributes very slowly. This leads to longer exposure of the material at relatively higher stresses than applied stress which results in creep cavity nucleation at the notch root region. This behaviour is typically observed in relatively brittle materials. Different creep rates across the notch root because of continuous change in cross-sectional area impose constraint to creep deformation to maintain the strain continuity, which facilitates creep cavitation.

The stresses around the notch redistribute during creep deformation and approach to a stationary state condition. Finite element (FE) analysis coupled with continuum damage mechanics (CDM) has been extensively used to understand the stress redistribution and damage accumulation across the notch under creep...
conditions. It has been observed that for every notch geometry, there is a skeletal point where the stresses are almost constant irrespective of the value of stress exponent ‘n’ in Norton’s creep law relating steady state creep rate \( (\dot{\varepsilon}) \) with applies stress \( (\sigma) \) as \( \dot{\varepsilon} = A\sigma^n \), with \( A \) and \( n \) are material constants. The stresses at skeletal point obtained from FE analysis have been used to characterize the deformation and failure behaviour of material under multiaxial state of stress. The creep rupture life under multiaxial state of stress can be expressed similar to uniaxial condition by replacing the applied stress with representative stress. Number of models has been proposed to account for the roles of different components of multiaxial stresses in governing the creep deformation, nucleation and growth of creep cavity and rupture life prediction of material under multiaxial state of stress. These models relate the different contributions of von-Mises and principal stresses in representative stress for prediction of creep rupture life under multiaxial state of stress.

Renewed interest are shown on ferritic steels due to their good thermo-physical properties, adequate high temperature oxidation resistance and mechanical properties and cost effectiveness compared to austenitic stainless steels. Ferritic steels are used in steam generator of Prototype Fast Breeder Reactor (PFBR) at Kalpakkam, fossil power plants, petrochemical industries and heat transport systems. Continuous demand for energy resulted in evolution of 2.25Cr-1Mo steel designated as ASTM Grade 22. Subsequently, 9Cr-1Mo (ASTM Grade 9) steel has been developed to improve high temperature oxidation resistance. Creep properties of the 9Cr-1Mo steel have been improved by alloying with niobium, vanadium and nitrogen (ASTM Grade 91). The Grade 91 steel derives its creep strength from intragranular \((V,Nb)(C,N)\) and intergranular \(M_{23}C_6\) on sub-boundaries and from the tempered martensitic lath structure with high dislocation density.
Literature on experiments and modeling of creep behaviour of materials in presence of relatively shallow notches are extensively available. However, little exist on the experiments and validation of such models for relatively sharper notches emphasizing the effect of systematic variation in notch sharpness and deformation characteristics of the materials. In the present investigation, effect of multiaxial state of stress on creep rupture behaviour of three different ferritic steels having different mechanical properties have been studied.

Responses to multiaxial state of stress on creep rupture behaviour of 2.25Cr-1Mo, 9Cr-1Mo and modified 9Cr-1Mo steels have been studied in this investigation. Multiaxial state of stress was incorporated in plain specimens 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. 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 create different multiaxial state of stresses in the notched specimens. 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 110 - 230 MPa and at 873 K on the plain and circumferentially U-notched specimens of the steels. Two notches, 20 mm apart, were introduced in the specimens for post-test metallographic investigation on un-failed notch for creep damage evaluation.

Finite element analysis of stress distribution across the notch throat plane during creep exposure has been carried out to understand creep rupture behaviour of the notched specimens. FE analysis was performed incorporating elasto-plastic-creep behaviour of the steels considering plastic deformation of the material represented by Holloman equation \( \sigma_t = K(\varepsilon_p)^n \) along with Norton’s creep \( \dot{\varepsilon} = A\sigma^n \)
deformation law. Creep and tensile properties required for FE analysis were obtained from the tests carried out on the plain specimens of the steels at 873 K. To assess the different extent of notch strengthening observed in different steels, FE analysis of stress distribution across the notch throat plane has been carried out on incorporating the tensile and creep deformation properties of the individual steels. Detailed FE analysis has also been carried out using continuum damage mechanics to predict the damage evolution and creep rupture life of the steels under uniaxial and multiaxial state of stress. 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. 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. The rupture life under multiaxial state of stress has been predicted based on representative stress considering the available models. Skeletal point concept was adopted for estimating the representative stress in notched specimens. The analysis of damage evolution across the notch was carried out based on FE-CDM to validate the experimentally observed variations in fractography under multiaxial state of stress in the different ferritic steels.

In this thesis, the experiments, results and the interpretations are consolidated in seven chapters. The chapter 1 gives a general introduction and detailed literature review pertaining to the present investigation. The chapter 2 deals with the materials, notch geometries, experimental procedures and steps involved in FE analysis and CDM. Results on the uniaxial tensile and creep behaviour of the materials are presented and discussed in Chapter 3. In Chapter 4, the effects of notch on creep
behaviour of the steels are presented and have been corroborated based on the finite element analysis of stress distribution across the notch on incorporating tensile and creep deformation behaviour of the materials. Chapter 5 deals with the effect of notch sharpness on creep behaviour of the steels and the results have been substantiated with the finite element analysis and fractographic investigation. Predictions of creep rupture life of the materials under multiaxial state of stress has been discussed in Chapter 6 on incorporating damage evolution based on finite element analysis coupled with continuum damage mechanics (FE-CDM). The overall conclusions highlighting the salient finding of the investigation along with the scope for future work are summarized in Chapter 7.