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Creep and Fatigue Behavior in Micro-alloyed Steels – A Review

Abstract: This is a study of microalloyed steels for power plants and reactors. Components operate at coal dust fire temperature or thermal states of reactors, prone to creep during its service. This is to assess remaining life after passage of valuable life by variation in microstructure, e.g. cavity formation. Precipitation at the sub-grain boundaries and grain interior has increased high temperature strength. Coarsening of these appears at the end of life. Variation of heat treatment like spheroidising in place of solutionizing has been responsive to deteriorate performance. Dislocation interplay with precipitate has been acceptable while interaction among dislocations to forest dislocation has been unacceptable. Dislocation assisted nucleation of precipitates of fine size has been found to strengthen steel by thermo-mechanical control process with in greater heating temperature and lower finish rolling temperature. High temperature performance of materials has been assessed by creep, accelerated creep, creep-fatigue and fatigue performances. Increasing temperature for increasing efficiency has correlated the phase transformation of steel. Fatigue performances have been included in creep properties of materials when intermittent shut down–shut up schedules are operated, e.g. peaking power plants.

Keywords: power plant, reactor, creep, fatigue, heat-resistant alloy, degradation of steel, ferrite steel, creep-fatigue, cast steels, rotor, turbine blades, thermo-mechanical loading

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1 Introduction

Steel is an alloy of iron and carbon. Carbon increases strength and lowers ductility of iron. High temperature properties of carbon steel have been increased by alloying with micro-additions of chromium, molybdenum, vanadium, niobium, etc. These elements has increased high temperature properties, e.g. hot hardness and strength, high temperature corrosion resistance, life at high temperature by restriction of phase transitions i.e. at the temperature of exposure. Steel after micro-additions is called microalloyed steel. Microalloyed steel has high temperature resistant as required in boiler or reactor for pipelines and wrapper material respectively. Presence of inclusions or non-metallic particles induces reduction of valuable life by cavity formation during service exposure. Therefore clean steel production is an important criterion. Developments of high temperature properties in these steels stem from the precipitation of carbides at the subgrain boundaries and grain interior. $M_{23}C_6$ precipitates are found at the subgrain boundaries and MC at the grain interior, where M is metal. End of service life is studied from the presence of cavities and interplay of dislocations. Cavities are characterized by number of cavity, their distribution, size, string of cavity formation, their coalescence and related crack formation. Dislocation interplay has been studied for density of dislocation, interplay with the carbides at early stage as dominated by interactions with precipitates and variation of dislocation density. Service exposure coarsens precipitates by Ostwald ripening, when coarser precipitates grow at the expense of smaller precipitates. This coarsening softens matrix. Therefore dislocations interact among themselves to produce forest of dislocation. These alloys are tested and extrapolated for determination of valuable life by prolonged creep, accelerated creep or creep rupture tests. Studies of fracture surfaces on tested specimens show dislocation accumulation near fracture surface and uniform distribution of dislocation away from the fracture surface. Failure of power plant components those operate above $0.4T_m$ has been accounted from the fluctuation of temperature of fire during service exposure. Creep tests at lower temperature produce information about life of components. Extrapolated tabulation of data based on observed data of creep test has been insufficient, if temperature of prior forging/heat treatment history of the material is taken at relatively lower temperature than temperature of service exposure.

Creep resistance has been increased by either precipitation strengthening or solid solution strengthening. Mo content in Fe-Mo alloys increase creep strength by remaining in solid solution, whereas CrMoV steel show precipitation of Mo and related depletion of Mo from solid solution. It has been found that boron initiate precipitation as well as restricts the coarsening effects of carbides at high temperature on prolonged exposure.

Creep fatigue conditions have been mutually accessible degradation mechanism. Both creep and fatigue process incorporates degradation after prolonged exposure. The composite definition stood as the time dependent repetitive reversal of stresses, where both stresses have been selected below yield strength of material.

Advanced compositions of power plant steel components have micro additions of V, W, Nb, Ti, N, B like elements. With respect to the conventional micro alloyed steel joints, stability has been achieved for welds during service exposure of large components for which pre and post weld heat treatments are difficult.

2 Cr-Mo-V steel (effects of creep)

Studies of microstructural behavior under creep conditions for pipe steels of boilers have emphasized on heat treatment. 15CrMoV 5 10 has been a heat resistant alloy containing high bainite, finely dispersed VCN and Mo_2C precipitates and small grain boundary carbides. Long term creep resistance of 15CrMoV 5 10 has been produced by inhibiting dislocation motion by segregation of Mo_2C-carbide precipitation at grain boundaries. The vanadium content has been within 0.19 to 0.35%. 15CrMoV 5 10 pipes have been used for power stations with output greater than 10,000 MW. Life of these pipes have been considered to be 150,000 hours. The property in favour has been existence of uniformly distributed precipitates in matrix, presence of uniformly distributed precipitates, smaller sizes of grain boundary precipitates, existence of dislocation mesh and sufficient stability in service exposure. Degradation of microstructure of CrMoV-steel by creep exposure has been found to be linked to carbide reaction, phase transformation, dissolution, re-precipitation and coarsening and matrix alteration. Evidences of long term embrittlement after cavity formation has been result of degradation of microstructure by creep exposure. Favourable creep behavior in 15CrMoV 5 10 has been ascribed to high amount of Mo, which has been present both as solid solution and deformation induced carbides at dislocation [1, 2].

Corrosion resistance and high temperature creep properties have been important properties which have been achieved from high-chromium group of stainless steel. Air cooled martensitic 12Cr-Mo-V grade of steel after tempering has shown creep-rupture strength in between low alloy steel and austenitic stainless steel. The cost has been intermediate between these two and therefore applicable to high temperature applications, e.g. high pressure steam tubing and pipe work. Fully martensitic structure has desired for best high temperature properties. So controls over possibility of δ-ferrite formation during heat treatment keep conventional balance between strength and ductility. Barraclogh and Gooch have investigated cause of premature life of superheater tubing of a coal-fired power station. Poor creep resistance of tubes has steamed from low solution temperature of tubes. This has been 1173–1223 K instead of specified 1293–1343 K. These after tempering have increased spheroidization further [3].

In power generation and process industries tempered martensitic 12Cr-Mo-V steels have been used as a corrosion resistant and high temperature strength bearing, critical components operating at temperatures upto 873 K under stress. Creep has restricted high temperature performances of 12Cr-Mo-V steel. Appearance of separate cavities, strings of cavities, micro- and macrocracks have appeared to form at grain boundaries, inclusions and sometimes grain interior. Slow macrocrack has been formed by initiation and propagation of single cavities over years. Cavities have appeared at end of secondary creep zone. Decrease in intercavity distance has formed cavity strings, which has appeared in tertiary creep zone. Coalescence of cavities has produced microcracks to indicate exhaustion of life of components. In case of 12Cr-Mo-V steel creep cavitation has controlled by cohesion between carbide and matrix. Stress concentration between carbide and matrix has produced decohesion between carbide and matrix. After linking, cavities have generated wedge cracks at grain boundary triple points in connection with grain boundary sliding or deformation, grain and intermartensitic lath boundaries due to intergranular dislocation movement and pile ups. Cavity nucleation has also appeared to prefer inclusions, e.g. sulphides, silicates and oxides. Sulpher concentration above solubility limit (>30 ppm) has weakened interface and facilitates cavity nucleation. Dominant or combined effects of grain boundary sliding, plastic deformation, strain induced vacancy generation and diffusion have involved secondary nucleation on carbides in prior austenite grain boundaries or martensite lath boundaries. Studies of designed life and remaining life have been assessed from creep life by microstructural changes and cavitations produced. These have been assessment of (1) number of cavities per unit area, mean cavity diameter and cavitated area fraction. These have been controlled by strain or time and increased linearly with strain. (2) Decrease in temperature or stress has prolonged time available for cavity initiation. Cavities have initiated at early stage of creep, e.g. 600 separate cavities per square millimeter, with a mean cavity diameter of 0.2 μm after 21 hours of exposure. This has been 3% of rupture life at 908 K and at an initial stress of 80 MNm^{-2}. Increase in number of cavities per unit area at rupture has been about three fold to that of lower stresses and lower temperature exposure. Diameter of cavity has been about twice that of lower temperature exposure. Cavity distribution has been uniform, away from rupture end whereas at rupture end cavities have accumulated as cracks [4].

Feasible techniques are non-destructive route of evaluation for remnant life assessment of fossile power plants. High creep strength in Cr-Mo-V steels have attributed from precipitation in steel. This strengthening has been lost by coarsening and cavitation. Yoshikuni Kadoya and Toru Goto have experienced long term creep strength on retired rotor specimens for 10^4 hours at temperature ranges from 773–948 K. The observations have been (1) delay in tertiary creep has been low at lower stresses. (2) Dislocation density in trans-granular fracture region has been more and non-uniform and at inter-granular fracture regions dislocation density has been less and uniform. (3) Existence of a transition stress to change fracture mode from transgranular to intergranular. (4) Orwan stress to start plastic deformation has certain proportionate relation to that of threshold stress. (5) Creep rupture ductility has been high at stress level greater than Orwan stress level, when dislocations interact to other dislocations to produce cluster of dislocation. No interaction of dislocation has been found with precipitates. (6) Low creep rupture ductility has been observed at stress level lower than Orwan stress. The intergranular sliding at slow rate has been found from interactions of dislocation with precipitates. (7) Service conditions have appeared below Orwan stress level [5].

3 Cr-Mo-V steel (effects of fatigue)

Power plant components operating at high temperature have been subjected to both thermal fluctuations, stress variation, shut up and shut down alterations. Life limitations have been creep-fatigue consequences at high temperature. Improvement in steam turbine rotor materials has been either alloy development or minimization of impurities in material. To simulate actual thermal stress histories of high temperature structural components, isothermal long term creep-fatigue and combined temperature-strain cycle tests have been carried out. For long term maintenance free running, tests have been carried out on newly developed cam and lever type and heat-actuator type machines. The alloy 1Cr-Mo-V has been tested for study of creep rupture ductility of long term regime to take materials degradation into account within 1 and 100 hours. Successful estimation by linear damage rule has been done on collected data from isothermal, symmetrical, triangular, slow-fast and strain holding tests [6].

Damage tolerant design of structural components has been led by macro-crack growth behavior of materials. Components operated in high cycle fatigue and very high cycle fatigue (>10^7 cycles) has consumed 90% of fatigue life by micro-crack initiation and nucleation. Slip-bands have been located for initiation of fatigue cracks those arose from local cyclic plasticity. At low loading amplitudes, cracks have initiated in components at microstructure heterogeneities and micro-defects. In long term regime mesoscale features, (e.g. grain and phase distribution) has been found to be responsible for fatigue failure. Cause behind fatigue failure of materials have been described by different ways, (i) Micromechanical perspectives about remote loading conditions in microstructure, (ii) Under small load amplitude damage and failure occurrence by strain localization, (iii) Relation between slip band formation and fatigue damage evolution, (iv) Variation of very high cycle fatigue life to micro-textured regions, (v) Differences in crack initiation behavior in composites based on special distribution of reinforcing phases, (vi) Constant fatigue limit in very high cycle fatigue regime due to deformation-induced martensitic transformation in an austenitic stainless steel, (vii) Fatigue mechanism from evidence about disappearance of fatigue limit and occurrence of subsurface crack initiation from micro-defects, (viii) Nucleation of fatigue cracks in very high cycle fatigue regime from non-metallic inclusions and porosities, (ix) Correlation of fatigue strength with micro-hardness, size and location of defect in long life regime. Author has suggested fatigue life estimation of low strength Cr-Mo-V steel at 643 K for long life axially push-pull fatigue tests. Effects of microstructures and micro-defects on long term fatigue behaviour to crack initiation have been as follows. (i) Appearance of duplex S-N curve with crack initiation transition from specimen surface to interior. Appearance of fish-eye areas on fracture surface that ascribed to local cyclic plasticity from heterogeneity of microstructure. (ii) Granular bainite has shown better fatigue performance than long lath bainite in high cycle fatigue regime. (iii) Dominance of inclusions for fatigue failure than microstructures has appeared in very high cycle fatigue regime [7].

Increasing temperature and stress amplitude have decreased fatigue life. At 543 K for a stress amplitude of 440 N/mm^2 a relative life time maximum due to strain aging process has been observed. Cyclic softening has been characteristic to cyclic deformation behavior in whole temperature range. In temperature range of dynamic strain aging, a maximum dislocation density has been observed. At constant stress amplitude, increasing number of cycles and temperatures, dislocation density has decreased [8].

Complex thermo-mechanical and metallurgical effects have appeared in structural components working at high temperature and cyclic conditions. Pressure of composite material, e.g. brake pads against friction surface of high speed trains have been subjected to simultaneous mechanical and thermal loadings. Brake discs have been equipped with high temperature resistant steel for trains at velocities of 270 km/h. Increase in speed upto 350 km/h increases energy dissipation by friction. Capacity of fatigue resistance of such structures has been affected by this speed. Transient thermal gradient exist in breaking equipment those have consisted of a brake disc, brake pad and friction area. Severe stresses and local and general plastic strains have been induced from high level of transient thermal gradients. This has caused introduction of residual stresses after cooling. Micro-cracks have appeared on friction area of damaged disc because of repeated breaking. Low cycle fatigue damage has been indicated by such brake discs. Complex physical phenomena of interaction have been (i) thermal exchange, (ii) viscous effect (creep, relaxation, effect of load rate), (iii) plastic strain memory effect, (iv) thermal expansion, (v) microstructural changes, (vi) cyclic softening and (vii) friction and wear. Behavior of steel used in brake disc has been modeled by anisothermal elastoviscoplastic concepts. Improvement and extension of mechanical capacity of brake discs has been illustrative in this model. Under thermomechanical cyclic loading, actual behavior of material has been modeled by a variable temperature elastoviscoplasticity concepts based on previous models conceptualized from thermoelasticity and thermoelastoplasticity effects. The additional effects considered in addition have been non-linear kinematic and isotropic hardening, viscoplasticity (creep, relaxation, effect of load rate) and the plastic strain memory effect. Author have referred to that proposed elastoviscoplastic model have been in good agreement with actual behavior of material with incorporation of strain memory terms and use of two isotropic hardening variables. Model includes microstructural changes beyond 908 K. Damage of brake discs has appeared from friction surface under pressure of brake pads affected by complex and repeated loading [9].

4 Cr-Mo-V-Nb steel (effects of fatigue)

Alternative to high temperature austenitic steel grades martensitic 9–12%Cr type of steel have been commonly used in both conventional and nuclear power plants. The properties in favour have lower thermal expansion and better thermal conductivity and reduced tendency to neutron-induced embrittlement. Selection of desired combination of strength and ductility has been possible by tempering effects on these alloys. Aging effects during service exposure has been evaluated from creep rupture curves. Wrapper material for fast breeder reactors has determined to harden at 1348 K for 30 minutes followed by tempering at 973 K for 2 hours. Temperature variation in reactor core between 1073–1173 K has been exceeding tempering temperature of initial state and transition temperature of 1053 K at which bcc to fcc transformation starts. Pronounced influence on creep rupture and creep behavior has appeared, if transient exceeds 1248 K region. Creep stability has been possible within 673–873 K. Explanation of author is based on findings obtained by creep rupture tests above 1073–1198 K [10].

Tensile strength and toughness of steel has been increased by grain refinement. When grain size of steels has decreased to one micron, Hall-Petch relation holds for yield strength and ultimate tensile strength. Normally tensile strength and fatigue strength has been proportional. For high strength steels, inclusions have played role in fatigue fracture processes. Inclusions in steel have been reduced greatly by secondary refining techniques. Few large inclusions have been decisive to induce fatigue strength decrement. Therefore to achieve higher tensile strength and fatigue strength, relation between grain size and inclusion size have to be harmonized. For automotive structures and components fine-grained high strength 42CrMoVNb steel have been used. Fatigue properties in these steels have been as follows: (i) Determination of conventional fatigue limits have not been possible because of absence of horizontal asymptotes in 10^6–10^7 regime. Alteration in prior grain size of smooth surface specimen has no monotonous change in tensile strength, whereas monotonous changes have appeared in tensile strength, (ii) Fatigue cracks have appeared to initiate at internal inclusions, surface inclusions and surface matrix, (iii)

Fatigue strength have complex influence to grain refinement. This has referred to specific grain size for improvement of fatigue strength. Inclusion size has specific relation to initiate fatigue cracks. Below this size fatigue crack has no relation for crack initiation [11].

5 V-Cr-Ni steel (effects of fatigue)

Excellent corrosion and wear resistance and high strength has been achieved in a new cast iron with vanadium carbide dispersed in an austenite matrix microstructure. As a structural material this iron has been used and as a replacement of spheroidal graphite iron. Fatigue studies of high V-Cr-Ni cast iron has shown contradictory role in fatigue behavior by vanadium carbide cluster. VC cluster has reported to initiate fatigue cracks as well as it has acted barrier to early small crack growth. Completed microstructure has been studied to understand role of microstructure present in this iron and optimization of microstructure. Material with different C and V content has been studied for microstructures and morphologies of vanadium carbide (VC) in high V-Cr-Ni cast iron. Effects of microstructure and VC speroidization on fatigue behavior have been discussed on the basis of small crack growth and fracture surface analysis. Analysis has summarized as follows: Fatigue strength has increased with non-spheroidal VC, proportionate increase of fatigue strength and lamellar structure, VC spheroidisation has not improved fatigue strength, and fatigue strength has been reduced by spheroidal VC than non-spheroidal VC. Petal like VC and fully lamellar structure has relatively more fatigue strength. Fatigue cracks have appeared to initiate at VC grain boundary region when VC was smaller in size, whereas coarser VC, e.g. petal like VC initiates fatigue cracks. Petal like VC has shown highest fatigue crack growth resistance. VC speroidization has not improved small crack growth resistance [12].

High V-Cr-Ni cast iron has contained similar proportions of Cr and Ni as in austenitic stainless steel and VC dispersion in whole matrix. This cast iron has been expected to replace traditional cast iron, e.g. nodular cast iron. High alloy element content has induced high strength, excellent static corrosion resistance and excellent wear resistant, which has been preferred to extensive applicability for industrial purpose. Corrosion resistance of this iron has been less than austenitic stainless steel. Increasing C and V content has decreased pitting potential in the material with non-spheroid vanadium carbides than that of cast iron bearing spheroid of vanadium carbide. Formation of corrosion pits has appeared at VC, lamellar structures, boundary between these phases and austenite matrix of microstructure. Carbides have been electrochemically poor compared with matrix microstructure. Fatigue tests have shown endurance limit below to that of laboratory air medium. This has been effects of premature crack initiation due to corrosion pit generation, growth and coalescence. Slow growths of small cracks in 3%NaCl aqueous solution have produced than in laboratory air. Corrosion pits has led the crack path attributing to complicated crack path [13].

6 Cr-W-V-Ta steel (effects of creep)

Microstructure evolution during creep test in 9Cr-2W-V-Ta steels and 9Cr-1Mo-V-Nb steels have referred deterioration of creep strength in Mo bearing steels. This has been accounted from localization of creep strain at zones of non-uniform distribution of Mo atoms. This has been activity of Laves phases which has been more prone to form in alloy system for Mo bearing steel than W bearing steel. Conventional heat-treatment of 9Cr-1Mo-0.2V-Nb steels show improvement by addition of W in place of Mo. W produces $M_{23}C_6$ phases whereas Mo produces Laves phases. This behavior has improved creep strength of W alloyed steel than Mo alloyed steel. No difference has been found in (1) lath size, (2) dislocation density of martensite, (3) size and amount of MX type precipitation and (4) solid solution hardening [14].

7 Cr-W-V-Nb (effects of creep)

Microstructure and creep rupture strength in low C-2.25Cr-1.6W-V-Nb steel has been described to be dependent on cooling rate. Of different cooling rates air-cooling from austenitization has showed improved creep properties because of transformation of bainitic ferrite to granular bainitic ferrite with polygonal ferrite. Boiler pressure parts with superior weldability and high temperature strength bearing capacity has been found to be better for low C-2.25Cr-1.6W-V-Nb steel than 2.25Cr-1Mo steel in thicker sections. The vanadium content is reported to be 0.23 to 0.26 and cooling rate of steel to be 0.09 K/s. Vanadium has reduced strain aging and strengthened steel by forming vanadium nitride. Balance between vanadium and nitrogen content for formation of vanadium nitride reduce nitrogen which is an impurity in steel during steel making. The vanadium nitride formation has enhanced at slow cooling rates [15].

8 Cr-Mo-Nb-V-N steel (effects of creep)

Creep behavior of 9Cr-Mo-Nb-V-N (T91) steel has been studied to be interplay of precipitation. These precipitates have been formed during high temperature services in power station equipments. Short term constant load creep tests and transmission electron microscopy (TEM) study on this alloy steel have produced precipitation of $M_{23}C_6$ (where M = Cr, Fe) and MX (where M = Nb, V and X = C, N). Creep exposure has coarsened these precipitates. A model has predicted that co-relation between effects of coarsening law; an applied stress has been a threshold stress that has been proportional to Orwan stress. This threshold stress of model has been due to strengthening effect of dispersed phases [16].

9Cr-Mo-Nb-V-N steel has been used for high temperature components for power plants. High operating temperature and pressure has improved thermal efficiency. These alloys have been tested within stress range of 2 to 350 MPa. Studies of heat treated (normalized and tempered) and creep tested specimens have shown elongated subgrains in heat treated state. Those have converted into course and equiaxed subgrains at a decrease in free dislocations. Heat treated subgrain boundaries and prior austenite grain boundaries have appeared to be sites of precipitation of large particles ($M_{23}C_6$, where M is Cr or Fe, size = 50–200 nm). During heat treatment or creep exposure precipitates (Nb and V carbonitrides of 10–50 nm size) have appeared at interior of subgrain boundaries. Microstructural features those have played role in creep behavior has been precipitation hardening, and subgrain growth. $M_{23}C_6$ particles contribute to stability of the initial subgrain structure by retarding subgrain growth. An additional source of strengthening has been observed from MX carbides and carbonitrides those have precipitated during tempering or creep. This strengthening has developed due to interaction between intragranular precipitates and dislocations. The steel has been tested under creep in the high stress regime to establish dislocation creep. At a stress exponent > 9 steel has showed presence of a threshold stress. Microstructural observation has been characterized by Ostwald ripening of precipitates at grain boundaries as well as grain interior. At early stages when there was no particle morphology variation, then it has predicted that Orwan stress generated both large and fine precipitates. Difference between applied stress and a threshold stress has been found to be proportional to Orwan stress generated by two families of particles at a stress exponent of 5 [17].

9 Ni-Cr-Mo-V steel (effects of fatigue)

Two components in contact and subjected under cyclic loading have referred to fretting fatigue. This failure has appeared in machines and structures, e.g. gas turbines, wheel shafts, bolted pipes, wire ropes and springs. Fretting induced fatigue has been susceptible in area of contact in blade/disc dovetail joints between blade and disc in turbines. In comparison to fatigue, in fretting-fatigue, fretting has acted as stress concentrator and then a flaw generator to produce premature crack nucleation. Fretting action has accelerated crack formation and propagation by tangential stress along contact surface and stresses near contact edge. Fretting fatigue has strongly depended on stress near contact edge. Stress states near contact edge have depended on contact pressure, relative slip, cyclic stress and rigidity of contact pad. Contact pad rigidity has referred to significant influence on relative slip, and stress state at contact edge. Effect of contact pad rigidity on fretting fatigue strength has been conducted for different pad heights. Author has concluded (i) Regardless of contact pad geometry increasing pad rigidity has increased relative slip amplitude at contact edge and maximum tangential stress range near contact edge, (ii) Complicated variation has showed between pad rigidity and maximum compressive stress range near contact edge. (iii) Fretting fatigue strength has depended on tangential stress range and compressive stress range, (iv) Fretting fatigue failure criterion has been reproduced by a fretting fatigue design curve. This has drawn from plots of tangential stress range versus compressive stress range diagram [18].

10 Mn-V-N steel (effects of fatigue)

Fatigue reliability and design of structures for long term services has been a matter of assurance of safety. This has been a cause of wide scatter band in data of fatigue properties under variable amplitude loading. Assessment of fatigue reliability of structures to date has been determination of fatigue strength from interference model of stress and fatigue strength. Using Miner's rule cumulative fatigue damage under variable amplitude loading has determined and probability distribution of fatigue strength of a specific structural detail has been derived from test results of identical detail under constant-amplitude loading based on so called equivalence assumption. Fatigue life of elements under variable amplitude loading has followed sometimes a log-normal distribution or an underdeveloped prediction about probability distribution of fatigue life. Author in this context has predicted probability distribution of fatigue life of low-carbon low alloy steel notched elements under variable amplitude loading, which may also be applicable in fatigue reliability assessment of structural members, welded structural members of high strength low-alloy steels. Three problems accepted by author has been (i) statistical analysis of the fatigue test results under constant-amplitude loading to obtain expressions for fatigue life with given survivability, (ii) rule for calculating cumulative fatigue damage under variable amplitude loading and (iii) Substantiating prediction of probability distribution of fatigue life that can be solved based on experiment. Test results for fatigue life of 15MnVN steel notched specimens at a given stress amplitude has followed log normal distribution. In non-continuous strain hardening characteristics, the fatigue life has been predicted by using Miner's rule without either accounting interaction effect between loads in load spectrum or load sequence effect. Values of equivalent stress amplitude in load spectrum have been lower than or equal to fatigue threshold or fatigue limit. This could be omitted in the life prediction of 15MnVN steel notch specimen [19].

11 Co-V steel (effects of fatigue)

In cyclically deformed cubic metals such as copper, nickel and iron documentation have referred to formation of persistent slip bands, extrusions and intrusions at crystal surfaces. Development of ladder substructure in copper and nickel single crystals has reported to be one of common varieties of dislocation substructure to change surface topography. In intermetallic compound i.e. $Ni_3Al + B$ crystals oriented for single slip, fatigue crack has taken place from persistent slip bands, extrusions and intrusions associated with crack initiation. In this alloy ladder structure has not been observed. Polycrystalline B_2 intermetallic FeCo-2%V have reported fatigue crack as transgranular crack initiation along slip bands, in both ordered and disordered condition and cycling under air or vacuum medium. Damage accumulation in polycrystalline FeCo-2%V to surface or sub-surface has described as follows: An exponential law has presented successfully to describe results of investigation that has been steady state flow stress and yield strength in precipitation hardened ferritic alloy [20].

12 Improvement in creep properties

At 873 K the 9Cr-1Mo-V-Nb-N steel has shown greater creep rupture strength (CRS) similar to the austenitic steels. More conductivity and low thermal expansion properties at temperature of service exposure have favoured this alloy in high temperature plants e.g. coal fired boilers. To increase power generating efficiency, boilers handle higher temperature and pressure. Authors have studied CRS by addition of W, Cu, Co and other elements with variation of chromium between 9–12%. Heat treatment studies to improve properties have optimized the normalizing temperature or by applying thermo-mechanical control process (TMCP). TMCP increases the CRS. This has been studied to discuss the governing factor and mechanisms for such improvement. CRS has been improved by raising the heating temperature and finish rolling temperature. Coherency strain around VN precipitates have increased through lattice expansion, which has developed from increased heating temperature. This has increased partition of Nb to VN. VN dispersion has appeared more finely through nucleation sites along dislocation at lower finish rolling temperature. This has improved CRS through decreased inter-precipitate distance. It has been observed that precipitation of NbN/VN complex has changed to dislocation assisted uniform precipitation of disc like (V, Nb)N precipitation at lower finish rolling temperature. Coarse precipitation morphology has changed to fine precipitation to harden steel. This has been achieved by successive rolling from a sufficiently high temperature [21].

13 Ferritic low alloy steel

After First World War the high temperature strength bearing steels have been developed. Alloying elements content has risen after war. The chronology of element addition has been low alloy 2.25%Cr-1%Mo steel to 9%Cr-1%Mo steel as a more corrosion and creep resistant steel. Realization of beneficial effects of vanadium has appeared in tubes and pipes of steel. Successful development of ferritic steels with higher creep resistance has been based on the structural evolution, strengthening and degradation processes occurring during creep exposure.

Potential strengthening mechanisms in high temperature exposure are precipitate strengthening and solution strengthening. In ferritic steel grades precipitate strengthening has appeared by one secondary phase. This has been vanadium carbide (V_4C_3) or vanadium carbonitride (VCN) in 0.5Cr-0.5Mo-0.3V alloys, while $M_{23}C_6$ in

12Cr-1Mo-0.3V alloys at low nitrogen content. In case of two secondary phase formation precipitate strengthening have been Mo_2C and Cr_7C_3 in 2.25Cr-1Mo steel or $M_{23}Cr$ and MX in 9Cr-1Mo-0.25V-0.05Nb-0.05N steel. Decrease in inter-particle spacing have shown increase in the proof stress at room temperature and creep rupture strength (CRS) at high temperature and decrease in the creep rate.

Solid solution strengthening of ferritic Fe-Mo steels has appeared from Mo addition. Increasing Mo content has decreased creep rate. Short term creep tests on Mo bearing steel have shown Mo content in solid solution. On the other hand CrMoV steel has shown increasing Mo content to deplete Mo from solid solution and form carbides. This has referred to growth of M_6C at the expense of the VX particles. This lowers creep rupture strength.

Boron addition increases hardenability of low alloy steels provided boron has remained in solid solution instead of forming boron nitride. Boron has induced carbide precipitation, their distribution and resistance to coarsening. Boron has formed borides in place of carbides. However nitrogen content in steel has produced high creep strength. High dimensional stability has been accounted from VN.

Author has concluded (1) Mo content in low alloy steels should be lowered to about 0.5 mass%, (2) in modified Cr steels Mo or Mo_{eq} should be only about 1 mass%, and (3) CRS of modified Cr steels is possible due to increasing nitrogen content or boron addition [22].

14 Effect of trace elements

Creep resistance has appeared to increase in an alloy of low C-Cr steel containing Mo, W, V and Nb. Creep strength about 1.8 times has increased in a 0.06C-2.25Cr-1.6W-0.1Mo-0.25V-0.05Nb ferritic steel than that of conventional 2.25Cr-1Mo steels. This steel has been used in as welded conditions without requiring pre-weld and post-weld heat treatments because of bainite structure without martensite phases, if carbon content has reduced. This steel have wide application in boiler materials replacing conventional Cr-Mo steel. Creep strength in present steel has characterized as (1) Higher creep strength has led by stabilization of the matrix. (2) Motion of dislocation has obstructed by fine MX carbonitrides, where $M = V$ and Nb, and $X = C$ and N. Difference in atomic radii of iron and tungsten have produced strengthening effects. Lower diffusion constant of W has delayed the grain boundary migration and subsequently has increased recrystallization temperature. Based on variation in heat treatment and operating temperature, this has produced various precipitates in this alloy. These complex precipitations of carbides have included $M_{23}C_6$, M_6C, M_7C_3, M_2C and M_3C. Change in nucleation site, stability of carbide phases and morphology have been interplay of carbon activity and interfacial energy. Trace elements like B and Mn have changed properties of precipitation of these alloys. Clarifications has included role of Mn and B on creep properties, microstructural stability from view point of carbide precipitation kinetics and alloy partitioning of 0.06C-2.25Cr-1.6W-0.1Mo-0.25V-0.05Nb steel. Mn has reduced creep rate to increase lifetime to rupture, while boron has delayed tertiary creep stage to increase life. Creep deformation has been controlled by MX, $M_{23}C_6$ and M_6C type of carbides. Creep resistance has been increased by MX through dislocation pinning effects. Presence of W concentration has induced evolution of M_6C from grain boundary precipitates $M_{23}C_6$ during tempering of this steel. Mn content has property to delay this evolution of M_6C precipitation resulting in more time of W to be in solution. B-content has stabilized $M_{23}(C, B)_6$ along grain boundaries to restrict grain boundary sliding and migrations and thereby dynamic recrystallization [23].

15 Advanced low alloy steels

Improved high temperature strength and superior resistance to high temperature corrosion have been required for construction of advanced thermal power plants. Advanced low alloy steels have small additions of alloying elements like V, W, Nb, Ti, N, B and reduction of carbon content below 0.1%. Enhanced alloying have improved mechanical properties and improved weldability without pre and post weld heat-treatments, e.g. large components. Chemical composition and microstructure of advanced low-alloy steel has been found to control creep properties. At a fixed chemical composition creep properties have improved by temperature and time of creep exposure in addition to previous heat treatment. A decrease in inter-particle (V_4C_3 and VCN) spacing has been found to increase both proof stress at room temperature and creep strength at elevated temperature. In other words creep rate has decreased. Solid solution strengthening has been increased by Mo and W content. Long term exposure at elevated temperatures has induced secondary hardening in these advanced ferritic steels. This secondary hardening has produced embrittlement of non-tempered welded joints. Extent of secondary hardening has depended on temperature and time of exposure. Weld joint brittleness has also depended on the operating temperature of weld.

Creep resistance in advanced low alloy steel has referred to limit the Mo_{eq} to 0.5% and increase in vanadium content to the stoichiometric ratio for vanadium carbide formation [24].

16 Short term creep process

Advanced power plants have used high temperature pipe work components made of 9Cr-1Mo-0.2V steel. This steel has good combination of high temperature creep strength, high corrosion cracking resistance, lower oxidation rate and good weldability. The evolutions of dislocation structure consisting of subgrain and free dislocations within subgrains have been investigated in creep behavior of 9Cr-1Mo-0.2V steel. Apparent stress exponent n strongly depend on temperature, increasing from 8 to 16 as the temperature has decreased from 923 to 823 K, whereas apparent activation energy Q has decreased as the stress has increased. This has thermal activation to detach dislocations from carbide precipitates. Similar studies on short term creep test data has shown an increase of apparent stress exponent from 9 to 14 as temperature decreased from 923 to 848 K, whereas activation energy varies between 815 to 680 kJ/mol for variation of stresses within 160–200 MPa respectively. Studies about microstructural evolution of 9Cr-1Mo-0.2V steel have referred to the stability of initial grain structure by $M_{23}C_6$ precipitates and high temperature stability from high vanadium carbides or carbonitrides of very fine sizes those arrest sub-grain growth and fine enough to interact to dislocation during creep exposure. Comparison between equilibrium calculations with kinetic models and creep test data have referred that neither M_2X precipitates nor an intermetallic Laves phase $(Fe, Cr)_2(Mo, W)$ which have been observed in 9Cr-1Mo-0.2V steel, except at a high Mo content or W additions.

The present model have achieved (1) application of stress has affected energy barrier to be overcome when a local region has been under transit and not just potential energy of the initial and final local states, (ii) model under elimination of temperature as a function because of linear relation between activation volume and test temperature, (iii) proposal of multiple creep mechanism under rate control (slowest) of stress dependence of activation energy [25].

17 Long term creep process

Planned life under creep conditions for large structures have been 2,50,000 hours. Fluctuations of stresses and temperatures in creep exposure of alloy steels have referred to the allowable creep strength for failure after 1,00,000 hours of service exposure. Extrapolation of short term test data for estimation of 1,00,000 hours of life following analyses have reported. Prediction of (i) minimum creep rate, (ii) times to various strains and (iii) creep lives for stress-temperature conditions causing failure in 1,000,000 hours and more have suggested. Although a transition from transgranular to intergranular fracture has appeared and tempered bainite microstructure that has evolved during creep exposure but allow rationalization and extrapolation of multi-batch creep data reported for 1Cr-1Mo-0.25V steel. Cost effective acquisition of long term creep design data have been analysis of results from tests lasting upto 5000 hours. This has been (i) to generate comprehensive multi-batch data sets of 1Cr-!Mo-0.25V steel, (ii) effective rationalization and extended extrapolation of creep and creep fracture properties. Transition from transgranular to intergranular fracture has not been a criterion. Instead a link of hardness values has recorded for fractured specimens in creep mechanism [26].

18 Creep equations

A model based on creep equation for 9Cr-1Mo-0.2V (P_{91} type) steel has been an improved stress dependent energy barrier model. Relevant creep equation for this steel has been reproduced from phenomenological analysis of creep test data under isothermal constant stress condition. A simple Arrhenius type power law constitutive model could not describe data of test under minimum creep strain rate. Creep behavior of this steel has been satisfactorily described by modified power law curve after incorporating the concept of threshold stress. Concept of threshold stress has not been a stable material parameter, which varies with temperature and/or stress. Extrapolation of data into ranges where experimental data are not available has rendered uncertain. Improved stress dependent energy barrier model has been proposed for second creep equation. The improvement of standard model assumed (i) application of a stress affects energy barrier to be overcome at a local transition zone from initial state to a creep state, and (ii) applying a simple power function of stress instead of a hyperbolic sine function. For entirely climb controlled creep process, value of stress exponent, $n = 5$ has been too high. Apparent activation energy has been approximately 510 to 545 KJ/mol. This has been considerably higher than the activation energy for lattice diffusion.

Here apparent activation energy for lattice self diffusion has been stress and temperature dependent in a slowest, dominating rate controlling process of multiple creep mechanism. Therefore extrapolation has been treated to be unreliable [27].

19 Ferritic steels in power plants

Development of creep resistant ferritic steels has produced higher efficiencies in advanced power plants. Steam temperature of about 898–923 K has been possible in 9–12%Cr steels with niobium addition. Niobium has accepted as new element for advanced power plant group of steels. Creep resistant steels mainly have been used in power plants and petrochemical industries, e.g. large forgings and castings have been used to build turbines, tubes, pipes, plates, and fittings requirements in pressure vessels. Specific applications have required specific property development, e.g. good hardenability for large turbine rotor, good weldability for tubing and pipings. Economic efficiency, design improvements and application of new and better steels have been aim to improve of power plant technology. Fossile fuel efficiency, plant efficiency, a decrease in CO_2 emission has been important issues [28].

20 Turbine cast steels – life assessment

Life assessment of turbine components in fossil fuel power plants has been estimation of remaining life in high temperature when used beyond nominal designed life. Thermal aging, creep and fatigue have induced accumulation of damage after thermal softening in Cr-Mo-V steels. Relations between hardness and creep properties have appeared in rotor forgings as well as cast components. These relations have applied to assess life of components/turbine rotor by non-destructive hardness measurement methods. Studies of creep properties have established creep life estimation for degraded Cr-Mo-V cast components from interrelation among hardness test, metallographic observation, creep rate tests and creep rupture tests. Investigations on long term use of 1.25Cr-1Mo-0.25V cast steel have been softening of cast components, e.g. casings, valves and nozzle box after long term service. Cause of softening has been coarsening of carbides and recovery of dislocation structure [29].

21 Turbine rotor steels – creep fracture and mechanical properties

Conditions of temperature and stress have changed the fracture mechanisms of metallic materials. Over a wide range of anticipated conditions, this has been use of bird's-eye view of variations or plots called fracture mechanism maps. These maps are plots of stress and temperature or stress and time. Variations of fracture mode of creep resistant steel in a complex fashion have located at boundary of fracture mechanism map. Precise creep fracture mechanism maps at creep fracture regimes have been requirement for proper design and manufacture as well as safe maintenance of high temperature equipments of heat resistant steels. Accumulation of service induced and damaged boiler and turbine components have been subjected to task of assessment about extent of damage and remaining useful life. Fluctuating parameters in services has varied the creep fracture mechanism. Creep fracture maps have stated to be reliable guide to meet objectives. Clarifications of creep fracture and damage accumulation has been an emergency requirement as for example huge turbine rotor turning at a high speed. The present context has reported about creep fracture map for illustrating creep fracture mechanism and its long term variations as per regional fluctuation of variables for a life of greater than 1,00,000 h.

Author has experienced fracture after creep damage of specimen of turbine rotor within 723–948 K and stress level 47–412 MPa. Three regimes of creep fracture mechanism in map have been (i) transgranular creep fracture covering a wide range, (ii) creep cavity induced intergranular fracture with low rupture ductility and recrystallization rupture with high rupture ductility due to dynamic recrystallization. At 848 K, increasing cavities with time along grain boundaries has produced transition from transgranular fracture to cavity induced intergranular fracture? Creep rate has accelerated at 873 K by recovery of dislocation structure. Grain boundary migration has activated after aggregation-induced coarsening and dissolution of grain boundary precipitates, together with rapid reduction in grain boundary segregation of impurities. Transition from creep cavity induced intergranular to transgranular creep fracture have appeared from suppression of growth of grain boundary cavities. Activation of grain boundary migration has produced recrystallization rupture in a higher temperature and longer time to rupture region. At temperature and stress conditions of around 773 K and 100 MPa under which Cr-Mo-V turbine rotor steel has operated that placed material in creep cavity-induced intergranular fracture regime at which creep cavities have easily formed. Creep fracture mechanism maps have been plotted on a stress–time to rupture coordinate system and on a stress-temperature coordinate system [30].

22 Turbine rotor steels – effect of surface crack propagation

Safety requirement and reliability of high temperature components in electric power production plants has entailed serious accidents in fossil power plants because of frequent start and stop for peaking load to that of nuclear power plants. Repetition of transient thermal stresses in these plants has become important to evaluate creep fatigue damage. Under creep fatigue conditions small cracks have initiated at early stage of life those propagate at later stages to cause failure. Hence for both new plant as well as operating plants creep failure have been studied based on crack propagation. Creep-fatigue conditions at high temperature have been investigated to study the crack propagation behavior and clarified by propagation law on the basis of non-linear fracture mechanics. Author have experienced in this context about effects of through and surface cracks in specimens of small and large sizes from steam turbine rotor 1Cr-1Mo-0.25V steels at 823 K under load control conditions. Experiments have been conducted to examine the applicability of a non-linear fracture mechanics parameter, creep J-integral range to creep crack propagation in cyclic loading.

In case of through crack propagation, this has justified applicability of fracture mechanics parameter to the creep-fatigue crack propagation on different sized specimens, where governing parameter has been difficult for one sized specimens. Strong dependence have found on specimen sizes in relationship between (i) crack propagation rate and maximum elastic stress intensity factor and (ii) crack propagation rate and maximum net section stress.

In case of surface crack propagation, electrical potential method complemented by beach mark method has monitored it about size and surface crack. Creep J-integral range has been correlated with crack propagation rate for both through crack and for surface crack. Numerical simulation of surface crack propagation has shown that the crack has approached a semicircular shape regardless of the initial crack shape [31].

23 Conclusions

Micro-alloyed steels are mostly applied for high temperature and stressed conditions. Power plants/boilers have been the primary consumer of these alloys. Temperature and stress conditions may be (i) continuously under a particular temperature & pressure, (ii) fluctuating combination of temperature and pressure, (iii) intermittent variation of system temperature, (iv) radioactive embrittlement effects at reaction temperature. Chromium, molybdenum and vanadium have been common micro-alloying metals. Developments of power plants have suggested that, efficiency may be increased by greater temperature of operation. Increasing boiler super-heater temperature and phase transition temperature for steel appear to be within same range. Therefore, importance of micro-addition involves crystallographic transition in steel. Similar effects have arisen during fluctuation of temperature in boilers, or fossil fuel plants requiring shut down and shut up operations for peaking of electrical power above base hydro-electric plants or nuclear power stations. This has been a complicated consequence that which micro-addition has been in favour or in disfavour in steel. Chromium is used for high temperature resistance, if remain in solid solution. Prolonged exposure converts Cr in solid solution to carbides, supposed to be segregated at grain boundary. This is degeneration of microaddition. Molybdenum is a carbide former in which $M_{23}C_6$ composition has pin down grain boundaries to restrict grain coarsening tendencies. Prolonged exposure has formed cavities at the precipitates because these are harder constituents and responsive for dislocation interplay. Vanadium reacts with nitrogen urgently, therefore V has treated as nitrogen scavenger. Vanadium produces nitride, carbide and carbo-nitride. This is used for very fine precipitation in the steel matrix. Fine carbides increase strength of steel by precipitation hardening through out matrices without degradation under condition of exploration, which has been devoid of any variation in parameters or fluctuation. Life estimation with detailed microstructural study was needed to understand the behavior of steel after long service exposure in addition to non-destructive tests.

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