SYNOPSIS

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Global warming is one of the most critical issues that need to be addressed for sustainable development in the 21st century. To mitigate the effects of the global warming, almost all countries have drafted various treaties and guidelines to meet target cuts in CO_2 emission. The fossil fuels are used to meet 78% of total global energy consumptions, and hence these are primary contributors to CO_2 emission, adding up to 93% of total global emission. In particular, the biggest contributor to CO_2 emission is coal, a fossil fuel, accounting for 43 % of total global emission, and it is being extensively used in power generation industry throughout the world, particularly in developing countries. One of the ways to meet the challenges associated with reduction in CO_2 emission by power generation industry is to increase the inlet temperature of the steam by adopting highly efficient super-critical (including advanced ultra-super-critical and ultra-super-critical) power plant technology. For example, an increment in the steam temperature of 20 ℃ will improve the relative thermal efficiency of a 680 MW power plant by 1%, leading to a life-time reduction in CO_2 emission by 0.8 million tons. However, the super-critical power plant needs components made of an improved material to sustain the raised steam conditions.

Steam turbine components are subjected to various stress fields, such as circumferential stress due to rotation, thrust stress due to the aerodynamics of working fluid, vibration from structure, etc., at an elevated temperature (and under a corrosive environment) for long durations. Creep is a critical damage mechanism at high temperatures. Since the operating life-time of power plants are usually 20 years, and many will be operating beyond their estimated life, it is important to evaluate the dominant degradation mechanism and the residual life of in-service components for better economic and reliability assessment. For making this work relevant in this context, an in-service turbine blade, made of ferritic steel was obtained from GE Power, Bangalore (India) for evaluating its creep properties and commenting on its residual life.

Creep in bending or bending creep is an innovative, unconventional method for evaluating creep properties of a material that alleviates many difficulties related a uniaxial creep, such as gripping, alignment, fabrication of complicated geometry, etc. Unlike uniaxial creep, one can fabricate many samples of the simple cantilever beam from a given volume of material to perform laboratory test in relatively shorter duration. It should be noted that steady state often reaches faster in bending creep experiments as compared to uniaxial creep tests. Accordingly, creep in bending was adopted in this study for evaluating the creep properties of turbine blade material. However, the state of stress in bending is more complex than uniaxial testing, which requires special attention, as prescribed in this study.

The design of the sample, cantilever beams with the common fixed end and other required fixtures were conceptualized in this study and, subsequently, fabricated using wire electron discharge machining (W-EDM) (see **Figure S1**). Bending creep experiments were performed at different steady state stresses, ranging from 200 to 500 MPa at 550 °C. Steady state strain rate at various stresses were determined, and creep exponent was calculated by plotting the steady state strain rate against steady state stress on log-log scale. The material showed a stress exponent of 8 under the tests conditions, suggesting dislocation climb based power-law creep mechanism. This value of stress exponent is consistent with the values often reported for 9-12% Cr ferritic steels. Uniaxial creep tests were also conducted under same conditions. The results of both experiments, bending and uniaxial creep, were compared, and they were observed to be in the good agreement at all stresses (see **Figure S2**). The experimental results also matched well with the results reported in the literature on 9-12% Cr ferrite/martensite steels. This further establishes bending creep as a valid technique for performing creep tests. Upon establishing the validity of the bending creep tests, Monkman-Grant rule was used to estimate the creep rupture time (or the residual life) for this material under these tests conditions.

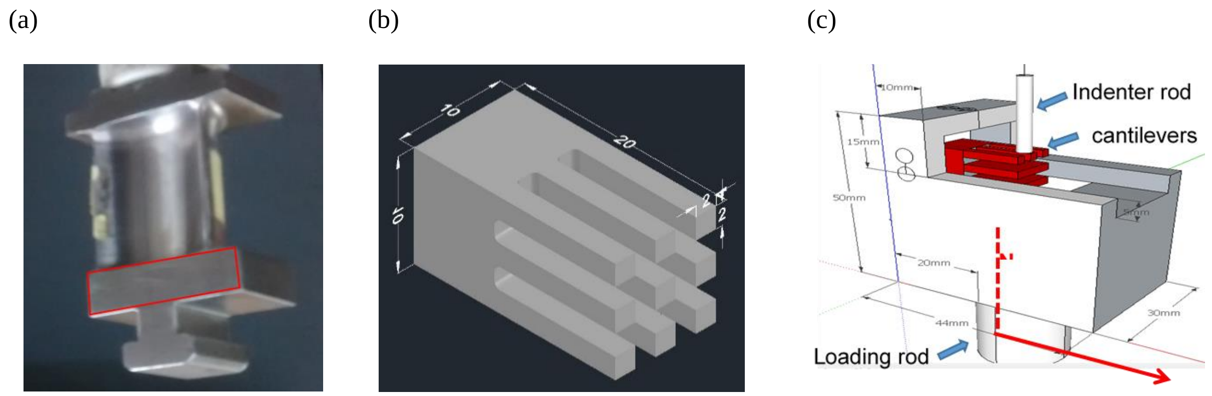


Figure S1: (a) A pictograph of the turbine blade supplied by the industry, and (b) schematic of cantilever beam samples fabricated from turbine blade. The cantilever samples were machined from the region shown in red color in (a). (c) Schematic diagram of experimental setup comprising the fixture, the sample and the indenter rod. All dimensions are in mm

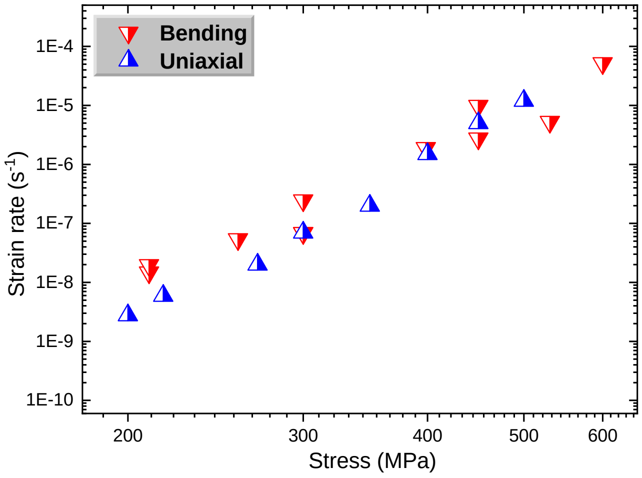
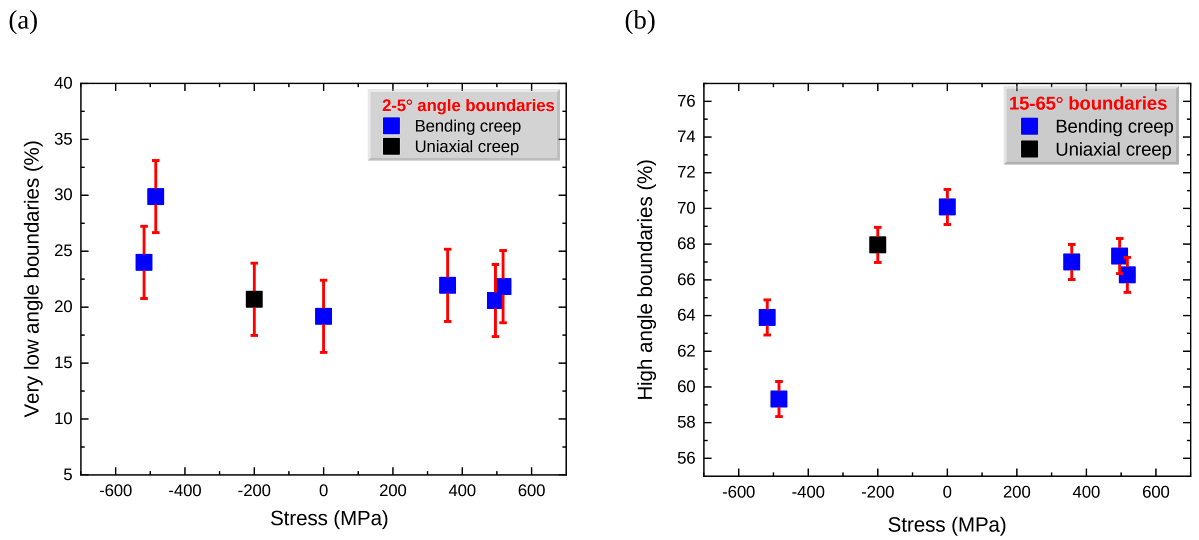


Figure S2: A comparison between the uniaxial creep and bending creep results based on the variation of the steady state strain rate as function of stress.

The microstructure was investigated using an optical and a scanning electron microscope (SEM), which revealed existence of prior austenite boundary, lath boundary, subgrain boundaries and alignment of various precipitates along boundaries in the material. Composition of the turbine blade steel material was estimated using electron probe micro-analyzer (EPMA). In the material, $M_{23}C_6$ carbides were observed to be dispersed along all types of boundaries, which provided strengthening against creep. In addition, $M_{23}C_6$ is known to apply Zener force on the boundaries, thereby retarding recovery, boundary migration and the grain growth. Electron backscattered diffraction (EBSD) analysis was performed at various locations in the tested beam to study the evolution of crystallographic texture and grain boundary misorientation angle with creep. The fraction of very low angle boundaries (2-5°) were observed to increase, while the fraction of high angle boundaries (15-65°) decreased during creep (see **Figure S3**). This suggests formation of subgrain during creep, which is expected. The density of geometrically necessary dislocations (GND), which were of the order of 10^{14} m^2, appeared to decrease with creep, wherein the decrease was more at higher stresses (see **Figure S3c**). The obtained results were compared with the literature on uniaxial creep of 9-12 % Cr ferritic steels, which was satisfactory, and a discussion on their implications is presented. Finally, nanoindentation tests on the creep tested cantilever samples were performed, which revealed a decrease in the pile-up height with the extent of the bending creep (see **Figure S4**). This suggests an increase in the strain hardening with creep, thereby suggesting recovery of the dislocation substructure. This is consistent with the decrease in the density of GND with creep.

Based on the results obtained in this study, it is concluded that bending creep has potential to become an alternative methodology for accurately evaluating the creep behavior, including microstructural evolution, of materials.



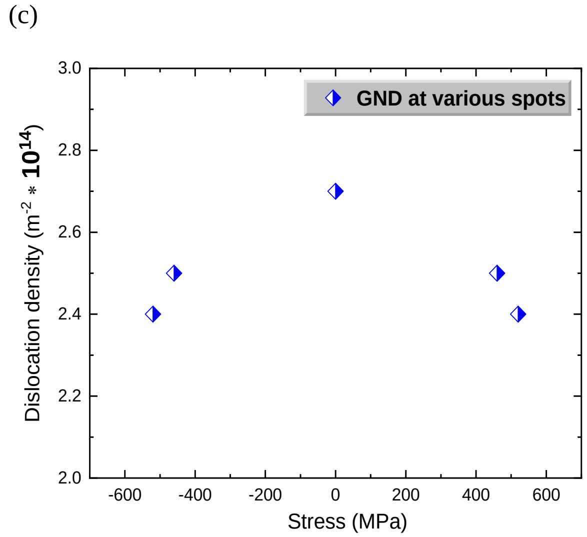


Figure S3: Variation of the fraction of boundaries as function of the steady state stress: (a) very low angle boundaries (2-5°), (b) high angle boundaries (15-65°). The standard error for each datum point was equal to that for the no-stress or free-end region. (c) Variation of density of GND (geometrically necessary dislocation) as function of the steady state stress during bending creep.

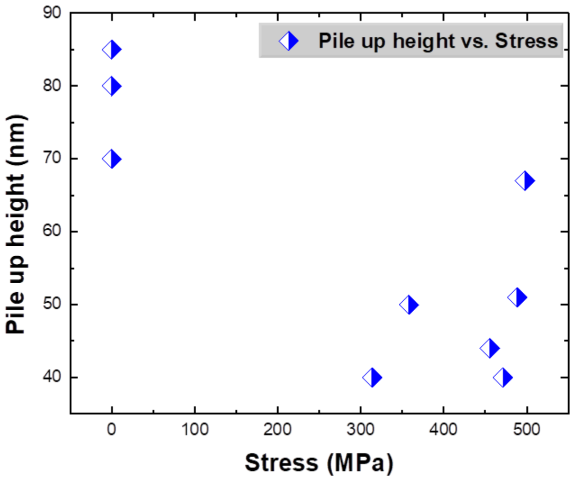


Figure S4: Variation of the maximum pile-up height as function of the steady state stress after bending creep.