Synopsis

Name of the student: Faizan Hijazi

Department: Materials Engineering, Indian Institute of Science Bangalore – 50012, India

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Title of the thesis: High-Throughput Bending Tests for Investigating Creep Behavior Affected by Structural and Microstructural Inhomogeneities

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The bending of cantilevers is an alternate test technique for the extraction of power-law creep parameters of materials. It has been shown that in homogeneous systems showing tension-compression symmetry, digital image correlation (DIC) can provide a route for evaluating creep parameters in a high-throughput fashion. Multiple stress-strain rate pairs could be obtained from a single test using the cantilever geometry that can easily be adapted for small samples also. The technique has been validated using miniaturized cantilevers of pure metallic systems and simple alloy systems. However, the materials for engineering applications are designed with complex, graded compositions and microstructures to achieve specific mechanical and thermal properties. These gradients, referred to as "inhomogeneities," could lead to complex stress-state and creep responses. In this work, the cantilever bending coupled with DIC has been extended to more complex systems that display large or small-scale microstructural gradients and tension-compression asymmetry.

In the first example, bending integrated with digital image correlation (DIC) and finite element analysis (FEA) demonstrates that creep deformation in a material primarily occurs in approximately 30% of the cantilever volume near the constrained end, especially when the power-law exponent ranges from 6 to 7 (**Fig. 1**)

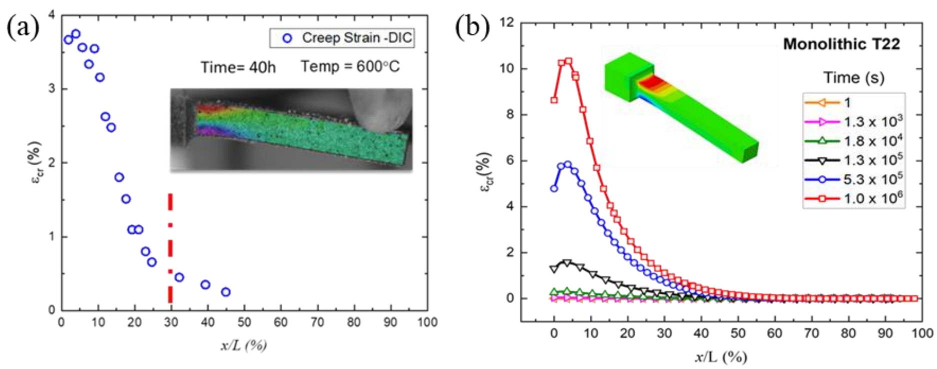

Fig. 1: Demonstration of the strain localization in a cantilever sample with a creep stress exponent, *n*, of 6, undergoing bending creep depicted: Strain distribution obtained (a) experimentally using DIC and (b) numerically using FEA.

As an approach to minimize the volume of material required for testing, the concept of fabricating composite cantilevers has been proposed and validated in this study (see **Fig. 2**). The composite cantilever consists of an 'active' creeping portion of T22 boiler steel (2.25Cr-1Mo) and an additively extended 'passive' non-creeping portion of IN-718. The reduction process involved varying the length of the T22 section, *a*, while keeping the total sample length, *L*, constant.

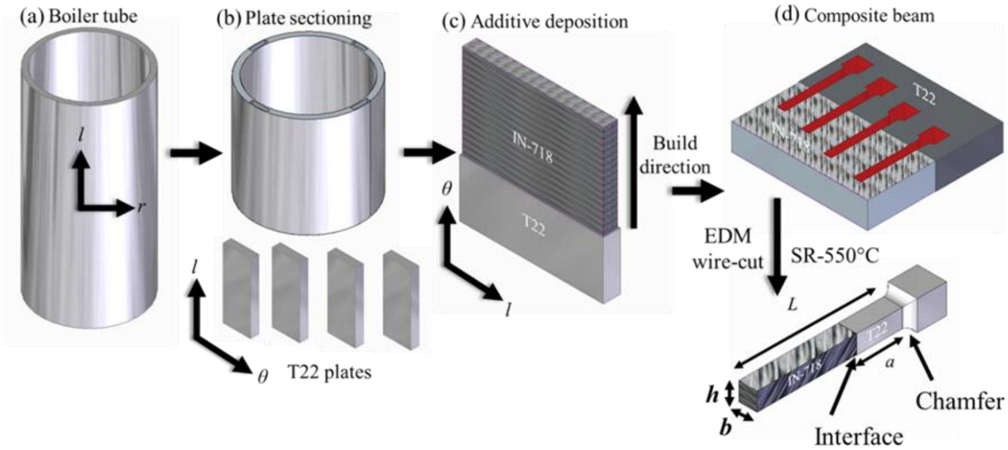

Fig. 2: Schematic illustration of (a) T22 boiler tube, received from BHEL and used as material for testing in this study, (b) sectioning of T22 tube in plate form, and (c) additive deposition of IN-718, (d) machining of composite cantilevers with varied *a/L* ratios, and bending creep setups: (e) load-point deflection with high-temperature fixture for sample gripping, indenter for loading

The DIC measurements conducted at 600 °C to assess the creep behavior revealed that non-linear analytical expressions for cantilevers could aptly predict the monolithic constitutive steady-state creep parameters from the composite cantilever if measurements are made at a critical distance away from the interface (see **Fig. 3a**). The difference in the steady-state creep rates in composite cantilevers with smaller "*a/L*" ratio is attributed to the effect of interface moving too close the chamfer, rendering the stress-state in the active volume indeterminate. To maintain compatibility in the deformation at the interface, additional stresses are generated in the active volume, leading to triaxiality. FEA indicates that accurate stress estimations enable predicting monolithic behavior using composite samples even with a small *a/L* ratio, with regions closer to the interface (see **Fig. 3b**).

Following the validation of this technique on as-fabricated steels, this approach was extended to service-exposed steels. The creep degradation in boiler steel that has been in service for ~ 240,000 h is ascertained using composite cantilevers with a small volume of "active" material (see **Fig. 4**).

Overall, this method achieves a reduction in the required material volume while preserving the bulk dimensions of the specimen, thereby finding a direct relevance to the residual life assessment (RLA) of bulk-sized components. Secondly, it opens new avenues of research focused on understanding localized deformation within materials with graded microstructures, presenting exciting opportunities for advancing our comprehension of the creep behavior of complex and graded engineering materials.

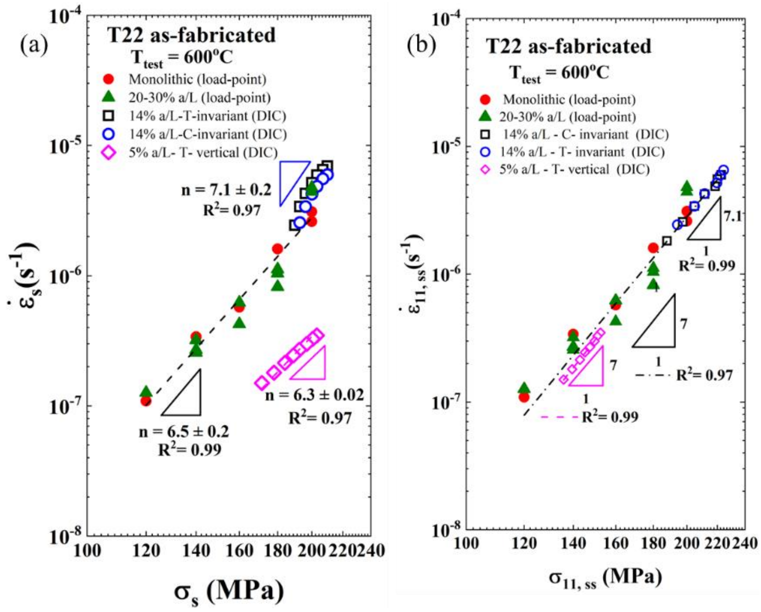

Fig. 3: Master plots showing the variation of steady-state strain rate with stress for monolithic and composite cantilevers with *a/L* ratios ranging from 30% to 5% with (a) analytically calculated stresses and (b) stress estimation from FEA for 5% and 14% a/L ratios.

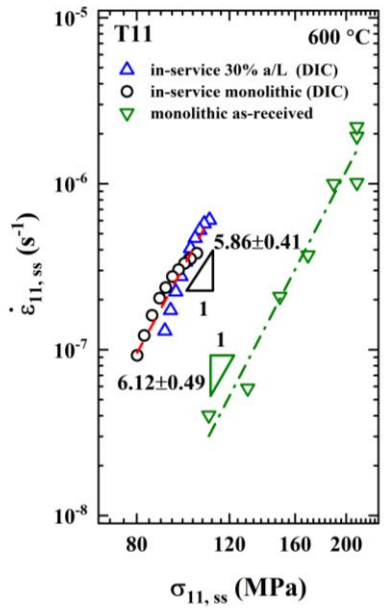

Fig. 4: Master plot showing the variation of steady-state strain rate with steady-state stress for composite (30% *a/L*) and monolithic cantilevers of service-exposed T11. For comparison, steady-state creep data obtained from as-fabricated T11 monolithic cantilevers is also shown.

The second example comes from a study of the influence of microstructurally textured regions (MTRs) in a rolled commercial Ti-6Al-4V alloy on its room temperature creep response at high stresses. Such macroscopic inhomogeneities lead to long-range strain localization owing to the non-uniform deformation. The cantilever bending was carried out in orthogonal directions with the specific predominant orientation of MTRs. The presence of extended $[10\bar{1}0]$ MTRs along the rolling direction (RD) leads to a shift in the neutral axis towards the other half of the cantilever (see **Fig. 5**). Microstructure correlations have been made using polarized light microscopy (PLM) as a high throughput method to correlate the presence of such MTRs with the creep behavior at room temperature.

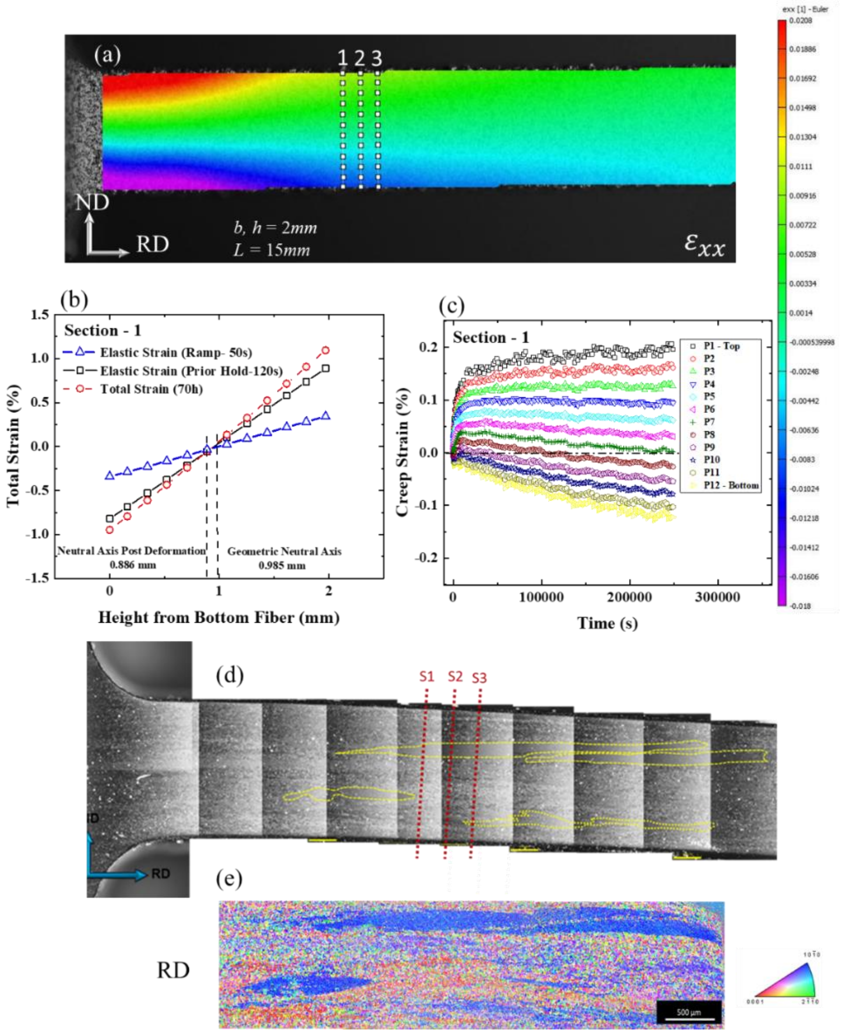

Fig. 5: DIC strain map in TD plane deformed along RD showing longitudinal strains ε_{xx} with three vertical sections 1, 2 and 3 (open squares) across the thickness and (b) representative strain evolution across thickness at time intervals corresponding to initial loading ramp (50 s), completion of loading (120 s) and completion of test (70 h or 250,000 s) and corresponding creep strain evolution with time showing tension-compression asymmetry at (c) Section-1.(d) PLM micrograph of the cantilever showing extended MTR in tension region of the beam with c-axis out-of-plane and Sections 1, 2 and 3 cutting through, and (d) the respective IPF showing the in-plane $[10\bar{1}0]$ orientation.

The innate tension-compression asymmetry in Ti for the $\underline{c}+\underline{a}$ dislocation glide is captured using the small-scale bending of samples at room temperature. The anisotropy and asymmetry in creep are readily brought out uniquely in a single experiment via the geometry of bending creep.

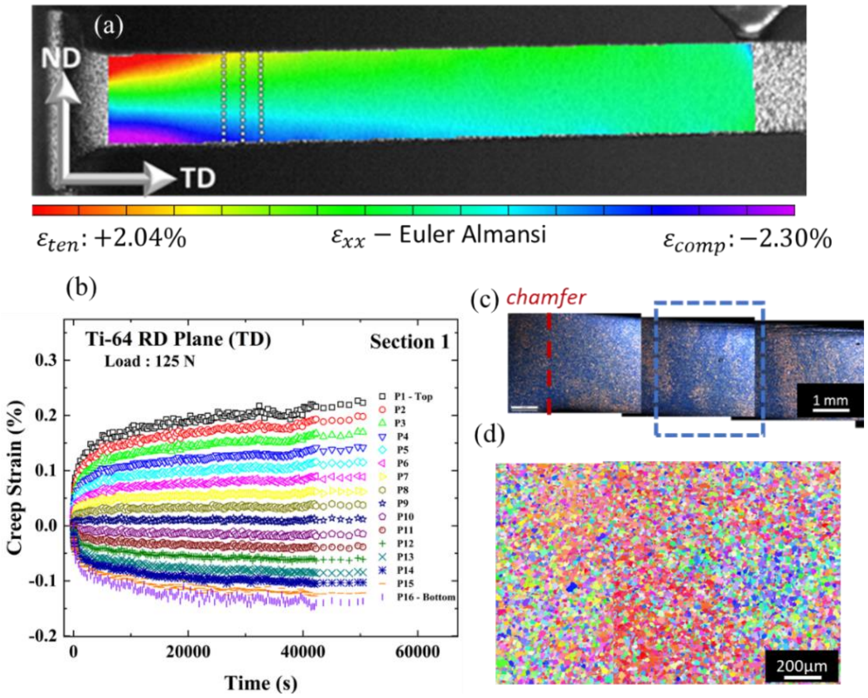

Fig. 6: Effect of MTRs along TD on the creep response of the cantilever sample: (a) DIC strain map in RD plane loaded along TD showing longitudinal strains ε_{xx}, (b) creep strain evolution in tension and compression at one vertical section highlighted in the strain map (i.e., a) and (c) PLM of post-test cantilever and (d) IPF of the highlighted region (dashed blue box) along TD.

Overall, these experiments serve as a foundation for the study of creep in complex engineering material systems with structural and microstructural inhomogeneities, such as weldments, composites, hybrid joints, etc. and residual life assessment and structural health monitoring.