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बहु पैमानों पर नाभिकीय संरचनात्मक पदार्थों का यांत्रिक परीक्षण

Mechanical Testing of Nuclear Structural Materials at Multiple Scales

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Understanding the mechanical behavior of structural materials used in nuclear systems requires comprehensive testing over a wide range of time, length, and temperature scales. In the Mechanical Metallurgy Division (MMD), extensive experimental programs are conducted to characterize materials such as zirconium alloys, austenitic and ferritic steels, refractory alloys, and nickel-based alloys. The generated database covers tensile, compression, creep, fatigue, and fracture properties across conditions simulating the extreme environments experienced in nuclear reactors. This multi-scale approach ensures that materials are qualified for safe, reliable, and long-term operation.

Mechanical Testing Across Time Scales

Mechanical behavior is highly dependent on the time scale of deformation, which is governed by the applied strain rate or frequency of loading. In MMD, tests span an exceptional range of strain rates over 11 orders of magnitude to study both quasi-static and dynamic deformation mechanisms. At the slowest rates, creep testing is performed at strain rates as low as 10^{-8} s^{-1}, capturing time-dependent plastic deformation over thousands of hours. Such long-duration experiments help assess the creep life and microstructural stability of zirconium alloys and nickel-based superalloys used in high-temperature reactor components. At intermediate rates (10^{-4}–10^{-2} s^{-1}), tensile and compression tests are carried out under controlled strain rates using servo-hydraulic and electromechanical testing machines. These tests provide baseline mechanical properties such as yield strength, ultimate tensile strength, and ductility at different temperatures. For high strain-rate behavior, the Split Hopkinson Pressure Bar (SHPB) facility enables testing up to 10^{3} s^{-1}, simulating transient loading conditions such as impact or seismic events that can occur in reactor systems. These studies are crucial for safety assessment under accident scenarios. In cyclic loading, fatigue testing is conducted over a wide frequency range—from 0.1 Hz in low-cycle fatigue (LCF) testing, where large plastic strains dominate, to 100 Hz in fatigue crack growth rate (FCGR) experiments, where small cyclic stresses drive subcritical crack propagation. Together, these tests provide a complete picture of time-dependent material degradation mechanisms.

Mechanical Testing Across Length Scales

Mechanical properties also depend on the length scale at which they are measured, from the microstructural to the component level. The MMD carries out testing from the nano- to macro-scale to correlate intrinsic material behavior with engineering performance. At the microscale, nanoindentation is employed to determine local hardness and modulus, enabling property mapping across grains, phases, and irradiated zones. This is particularly valuable for studying radiation-induced hardening in zirconium and steel cladding materials. Progressing to the mesoscale, miniature tensile testing is performed on small specimens machined from irradiated or limited-volume materials. These tests, often with gauge lengths of a few millimeters, allow evaluation of mechanical properties without compromising radioactive safety or consuming large quantities of valuable materials. At the macroscale, standard tensile, compression, and fracture toughness testing is performed as per ASTM standards to provide design-relevant mechanical data. The results serve as benchmarks for validating predictive models and supporting structural integrity assessments. Finally, component-level tests are performed to simulate actual service conditions. Examples include burst testing and pull-out testing of one-meter-long zirconium alloy tubes to evaluate deformation and failure under internal pressurization and mechanical loading. These large-scale experiments bridge the gap between laboratory-scale measurements and reactor component performance.

Mechanical Testing Across Temperature Scales

Temperature exerts a profound influence on the deformation and fracture behavior of materials. In nuclear reactors, components experience extreme thermal environments ranging from cryogenic to high-temperature conditions, and MMD's facilities are equipped to cover this entire spectrum. At low temperatures, Charpy impact and fracture toughness tests are conducted down to –150 °C to assess the ductile-to-brittle transition behavior of steels and weldments. Such data are critical for evaluating reactor pressure vessel steels and ensuring their toughness during start-up or shutdown conditions. At ambient and intermediate temperatures (25–400 °C), conventional tensile, compression

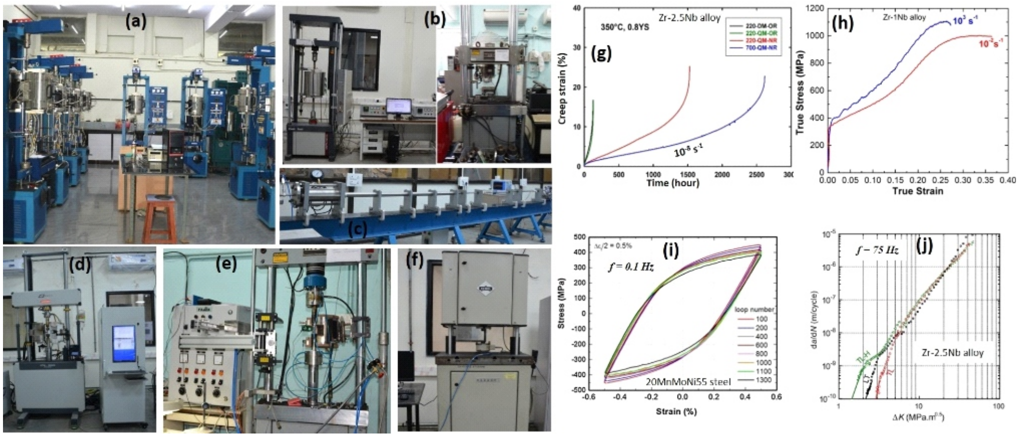

Fig.1: Representative facilities for time-scale testing: (a) Creep testing machines for testing at strain rate range of 10^{-8} to 10^{-4} s^{-1}. (b) Universal testing machines for testing at strain rates 10^{-5} to 10^{2} s^{-1}. (c) Split Hopkinson Pressure Bar for testing at strain rates 10^{2} to $8x10^{3}$ s^{-1}. (d) Servo Electric low cycle fatigue machine for cyclic testing in the range of 0.1 to 2 Hz (e) Servo hydraulic universal testing machine for cyclic testing in the range 0.1 to 20 Hz (f)Resonant fatigue machine for cyclic testing in the range of 1 to 100 Hz (g) Creep data of Zr2.5Nb pressure tube material- strain rate ~ 10^{-8} s^{-1} (h) Compression data of Zr-2Nb alloy at strain rate of 10^{-2} and 10^{3} s^{-1}(i) LCF data of 20MnMoNi55 steel at frequency 0.1 Hz and (j) FCGR data of Zr2.5Nb alloy at frequency 75 Hz.

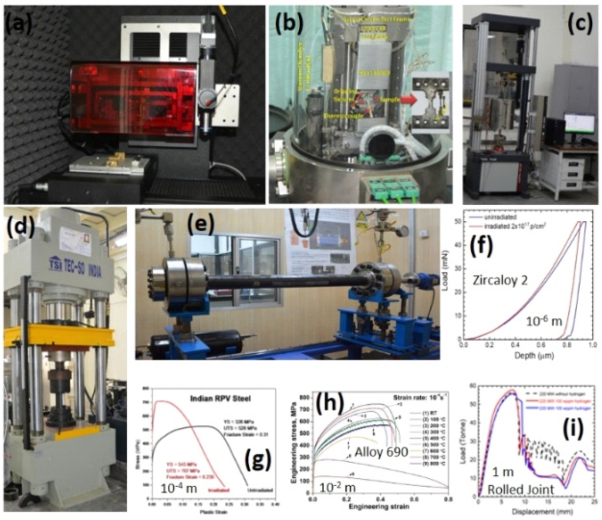

Fig.2: Examples of tests across length scales: (a) Nanoindentation setup, (b) Miniature tensile testing frame (c) Standard size specimen universal testing machine (d) 300 Ton press for component testing (e) Tube internal pressurization facility (f) Representative nanoindentation load-displacement plots for irradiated Zircaloy 2 at length scale of 10^{-6} m (g) Miniature tensile test data of irradiated RPV steel at length scale of 10^{-4} m (h) Tensile data of alloy 690 at length scale of 10^{-2} m (i) Zr2.5Nb PT-SS403 End fitting rolled joint pull out data at length scale of 1 m.

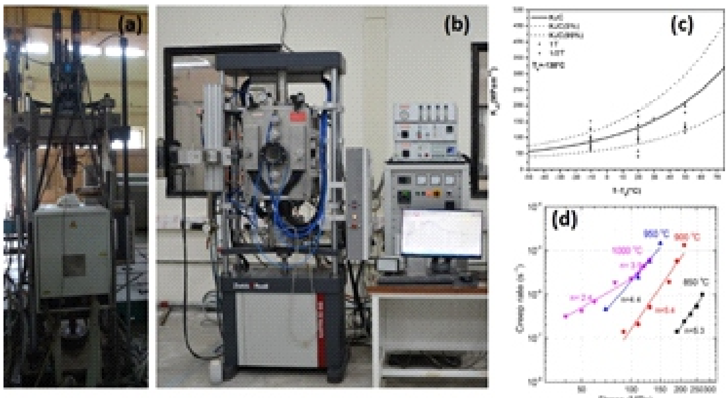

Fig.3: Mechanical testing across temperature scales: (a) Low-temperature testing chamber, (b) Elevated-temperature creep testing setup, (c) Master curve of reactor pressure vessel steel generated fracture toughness testing at temperature scale of -15^{0}C (d) high temperature creep data generated for a refractory alloy at temperature scale of 100^{0}C.

and fatigue tests are performed to evaluate in-service mechanical performance. These conditions correspond to normal reactor operation and transient loading scenarios. At high temperatures, creep and tensile/compression testing is conducted up to 1200 °C using vacuum or inert-gas furnaces. These experiments help in understanding creep rupture behavior, grain boundary sliding, and oxidation effects in nickel-based alloys and refractory materials designed for advanced reactor systems. This wide thermal testing range ensures reliable prediction of material performance across operating and accident scenarios, supporting both design and life-extension of nuclear components.

Conclusion

The Mechanical Metallurgy Division of BARC has developed an extensive experimental framework for characterizing nuclear structural materials across time, length, and temperature scales. The integration of nanoindentation, miniature testing, high strain-rate experiments, and elevated-temperature creep studies provides a comprehensive understanding of material behavior under service-like conditions. The resulting multi-scale mechanical property database serves as a cornerstone for materials design, safety evaluation, and structural integrity assessment of critical nuclear components, contributing to the reliability and advancement of India's nuclear energy program.