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Creep-fatigue Interaction Testing

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Fatigue lives in metals are nominally time independent below $0.5\ T_{melt}$. At higher temperatures, fatigue lives are altered due to time-dependent, thermally activated creep. Conversely, creep rates are altered by superimposed fatigue loading. Creep and fatigue generally interact synergistically to reduce material lifetime. Their interaction, therefore, is of importance to structural durability of high-temperature structures such as nuclear reactors, reusable rocket engines, gas turbine engines, terrestrial steam turbines, pressure vessel and piping components, casting dies, molds for plastics, and pollution control devices. Safety and life-cycle costs force designers to quantify these interactions. Analytical and experimental approaches to creep-fatigue began in the era following World War II. In this article experimental and life prediction approaches are reviewed for assessing creep-fatigue interactions of metallic materials. Mechanistic models are also discussed briefly.

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1. Test Facilities

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Modern creep-fatigue testing facilities are sophisticated closed-loop, servo-controlled, electro-hydraulic fatigue testing machines (Halford et al. 2000) adapted to high-temperature operation (Fig. 1). Typical machines consist of two or four posts, a rigid loading frame, and a hydraulic cylinder mounted in the center of the base. The cylinder transmits hydraulic pressure from a pump through an electronic servovalve. A specimen grip is mounted on the upper end of the cylinder ram, and another is attached to a load cell mounted to the upper cross member to measure axial load transmitted through the specimen. Modern grips utilize hydraulics to align and secure the specimen. Alignment of the specimen and loading axes is important to minimize bending loads and avoid buckling. Specimens have a uniformly reduced cross-section that is as uniformly heated as possible and experiences the cyclic stresses and strains. Cyclic strains are measured and controlled with commercially available extensometers with resolutions on the order of 10 microstrain.

A specimen heating system is the core of high-temperature testing. Test machine components such as the extensometer sensing element, specimen grips, load cell, and all hydraulic components must be kept cool. The most versatile heating system uses induction coils surrounding the specimen. High-frequency current passing through the coils induces eddy currents at the surface of the specimen. Specimen heating results. The high thermal conductivity of most alloys results in a specimen with minimal thermal gradients in the radial direction. Coil spacing controls axial thermal gradients. Three independently controlled coils can be

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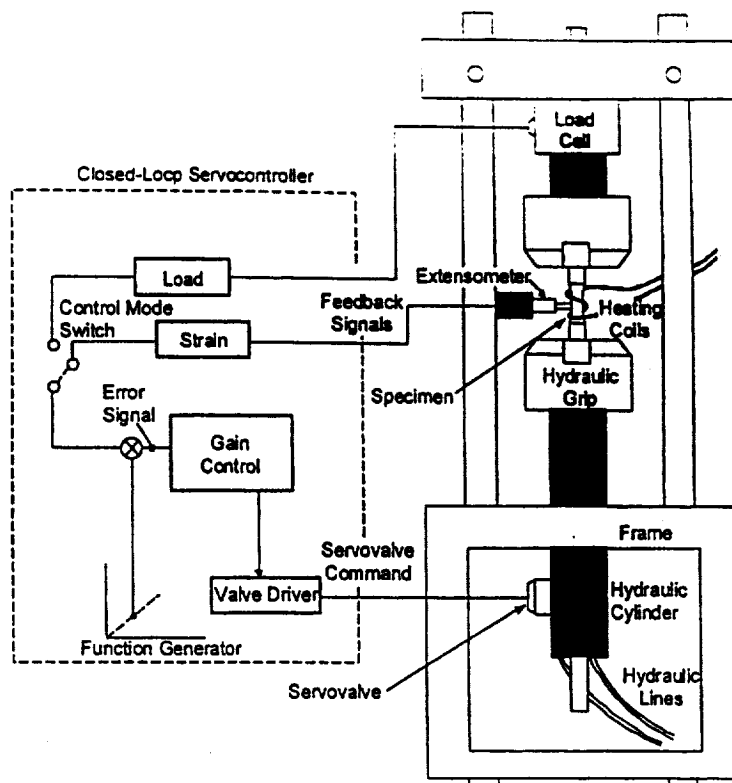
Figure 1

Modern creep-fatigue testing machine.

employed to minimize the axial thermal gradient. Coil spacing will allow visual observation of the specimen and permits attachment of an extensometer sporting ceramic extension rods that transmit gage section displacements to the more distant sensing element. A thermocouple held in direct contact with the specimen surface supplies feedback for temperature control. Commercial noncontacting optical pyrometers are also available. Alternate heating techniques, such as a combination of induction and radiation, are required for low conductivity materials such as ceramics. A small metallic susceptor surrounds the specimen and is heated by induction. The susceptor then radiates heat to the specimen. The low thermal mass of this system permits reasonably fast temperature changes. Radiation furnaces are quite common. They use coiled Nichrome wire or silicon carbide elements or even banks of quartz lamps. Furnaces offer high thermal stability because of the large thermal mass, but are slow to respond to intentional temperature changes during thermomechanical testing. Direct resistance heating also has been used successfully, but remains uncommon. High current (low voltage) passed

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through the specimen results in self-heating due to the specimen's electrical resistivity. This technique is the most difficult to control because of the inherently high thermal response. Heating of the test section does not rely on the thermal conductivity of the specimen; cooling, however, does. Maintaining an accurate constant temperature is difficult.

Modern test facilities are typically inappropriate for long-term ($\geqslant 1$ month) testing. Less expensive, more reliable, screw-driven machines are superior for this purpose. If long-term creep-fatigue resistance is a design requirement, long-term test results are necessary to verify life prediction models for accurate extrapolation.   sx0030

2. Mechanisms and Life Prediction Models   sx0035

Fatigue crack initiation and early growth mechanisms differ substantially from those for creep cracking. Fatigue damage is time-independent to-and-fro crystallographic slip, most evident at free surfaces. Creep damage occurs throughout the volume of stressed material and requires the thermally activated diffusion of atomic vacancies. Creep damage due to grain boundary sliding, however, intersects free surfaces in much the same way as fatigue slip.

The addition of creep to an otherwise pure tension/ compression fatigue cycle can be accomplished in three distinctly different ways as shown below. A baseline condition of pure fatigue cycling will have negligible creep present if a high enough cyclic frequency ($\geqslant 1\,\mathrm{Hz}$) is imposed.   sx0040

– Constant straining rate low enough to introduce creep in addition to crystallographic slip.

– Constant stress as creep occurs with time.

– Constant total strain while stress relaxes, converting elastic to creep strain (left panels of Fig. 2).

Since any one of these three ways of introducing creep into a cycle could be applied to tension only, compression only, or both tension and compression, there emerge, in the extreme, only four basic combinations of completely reversed creep-fatigue stress–strain cycles: sx0045

– Tensile plastic strain (p) reversed by compressive plastic strain (p), i.e., (pp)

– Tensile plastic strain (p) reversed by compressive creep strain (c), i.e., (pc)

– Tensile creep strain (c) reversed by compressive creep strain (c), i.e., (cp)

– Tensile creep strain (c) reversed by compressive plastic strain (p), i.e., (cc)

The right panels of Fig. 2 illustrate typical stress–strain hysteresis loops for strain hold type cycles. Invariably creep-fatigue cycles involve (pp) straining in addition to (cp), (pc), or (cc) components. Such cycles demand use of servo-controlled systems with extensometers and state-of-the-art function gener-   sx0050
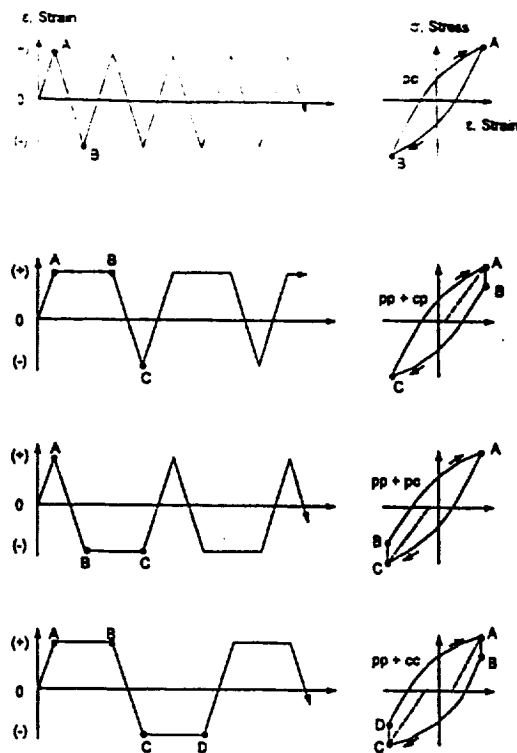
Figure 2
Creep-fatigue test cycles.

ators. The cycles are simplifications of actual complex service cycles. Experimental replication of service histories would require complex programming achievable through a computer-controlled servo system. Usually, life prediction models are relied upon to link simple laboratory cycles with realistic service cycles.

The deformation, crack initiation, and early growth mechanisms, in general, will be different for each of these discrete cycles. Schematic models developed to illustrate these differences have been compared to experimental observations for a variety of alloys (Manson and Halford 1984). Of the more than 100 creep-fatigue life prediction models proposed since the 1950s, only about 10% have been applied extensively enough to warrant their review (Miller 1984, Halford et al. 2000). The three most widely used are the time- and cycle-fraction rule (ASME 1986), strainrange partitioning (SRP), and damage mechanics. Few specifically address inevitable oxidation interactions. The ASME Code Case is extremely conservative and does not directly address when failure would occur. That condition is acceptable because power plants do not have the same stringent weight and performance requirements as, for example, aerospace propulsion

systems. The latter require much greater life prediction accuracy to conserve weight while maximizing a combination of durability and performance.

3. Concluding Remarks

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Creep-fatigue interaction is reasonably well understood at the phenomenological level. A significant short-term experimental database exists and several satisfactory analytic models are in use for estimating cyclic lives. Modeling of oxidation interactions with creep-fatigue, lack of long-term databases, and verified long-term extrapolation procedures remain as important areas of research.

See also: Creep-Fatigue: Oxidation Interactions

Creep-Fatigue: Oxidation Interactions

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