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STIRLING ENGINE - AVAILABLE TOOLS FOR LONG-LIFE ASSESSMENT

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Abstract

A review is presented of the durability approaches applicable to long-time life assessment of Stirling engine hot-section components. The crucial elements are: (i) experimental techniques for generating long-time materials property data (both monotonic and cyclic flow and failure properties), (ii) analytic representations of slow strain rate material stress-strain response characteristics (monotonic and cyclic constitutive relations) at high temperatures and low stresses and strains, (iii) analytic creep-fatigue-environmental interaction life prediction methods applicable to long lifetimes at high temperatures and small stresses and strains, and (iv) experimental verification of life predictions. Long-lifetime design criteria for materials of interest are woefully lacking. Designing against failures due to creep, creep-rupture, fatigue, environmental attack, and creep-fatigue-environmental interaction will require considerable extrapolation. Viscoplastic constitutive models and time-temperature parameters will have to be calibrated for the hot-section materials of interest. Analysis combined with limited verification testing in a short-time regime will be required to build confidence in long-term durability models. A strong need exists for improved long-lifetime durability models.

BACKGROUND

Today's spacecraft consume relatively low power levels, supplied by state-of-the-art solar arrays and storage batteries. Tomorrow's power needs will increase significantly as space-based missions evolve. Dynamic nuclear power systems utilizing the Stirling cycle show promise in meeting these needs.

Space power generation systems have stringent design requirements. They must be safe to launch and deploy, be reliable when called upon, exhibit a high efficiency-to-mass ratio, be economically feasible, and have long-time structural durability. Obvious trade-offs must be addressed amongst these requirements. In particular, low mass versus high durability trade-offs are of intense concern for high-temperature, life-limiting components such as the heater head of a Stirling engine.

The NASA-Lewis Stirling Space Power Converter (SSPC) Program considers using a geometrically complex hot-section heater head referred to as a "starfish" heater head, figure 1. Decreasing the thickness of the finned

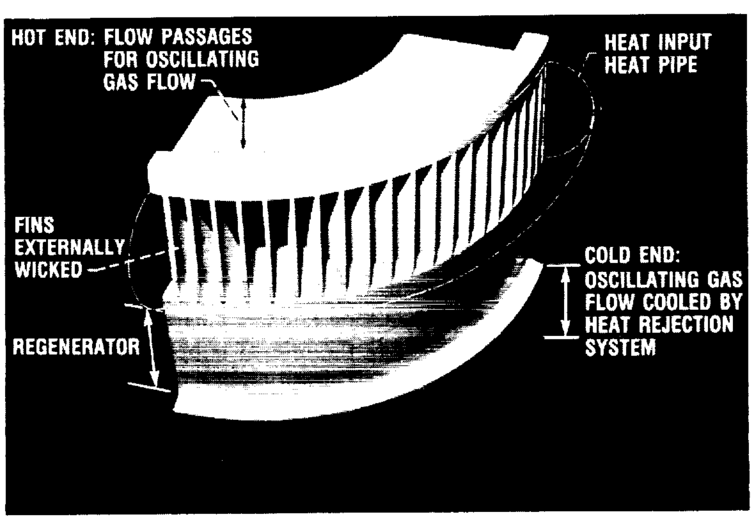

FIGURE 1. Section of "Starfish" Stirling Engine Heater Head Showing Thin-Walled Fins

walls will result in higher thermal efficiency and lower mass, but durability will be compromised as primary stresses within the wall increase. Conversely, increasing the wall thickness will provide greater durability with a decrease in efficiency and increase in mass. An optimal thickness can be arrived at only if the long-life durability relations are known with sufficient accuracy. The established lifetime must, of course, be sufficiently long to warrant investment of funds for design, construction, and deployment.

INTRODUCTION TO LONG-TERM DURABILITY

Stirling engine operating temperatures surpass 950 K and operational periods approach 60,000 hr which severely limits the strength capabilities of even the most temperature-resistant alloys. Finite lives will result eventually from the individual or interactions of creep, fatigue, and environmental degradation. Quantifying individual actions or interactive lives in the long-lifetime regime is traditionally done by conducting long-lifetime experiments on material samples under well-monitored and controlled laboratory conditions of temperature, stress, strain, and strain rate. However, time and resources are currently unavailable to generate a database of this type. Approximation procedures will thus have to be used to estimate the material characteristics.

Once material durability properties have been established by estimation or measurement, it becomes necessary to compute the local structural temperatures, stresses, strains, strain rates, etc. using classical mechanics of materials models (MMM) or finite element methods (FEM). At high operating temperatures for extended periods of time, material response will invariably deviate from linear elastic behavior, necessitating inelastic analyses, and most likely, time-dependent viscoplastic analysis.

Currently, long-lifetime durability assessment methodology is woefully inadequate for accurate prediction of component structural lives. Hence, optimal trade-offs of efficiency, mass, and cost cannot be determined with a high degree of confidence. This is particularly true for the relatively new, high-strength alloys currently under consideration for use.

FAILURE CRITERIA AND LONG-LIFE ASSESSMENT

The only readily-available, generally-accepted, high-temperature structural design code in the United States' public domain is ASME Code Case N-47 (Anon. 1987). Developed for the design assessment of terrestrial-based nuclear fueled electric power generation plants, the code embraces failure modes due to yielding, ratchetting, over-load, creep, creep-rupture, fatigue, and creep-fatigue interaction. The basic creep-fatigue model represents the state of high-temperature fatigue life prediction technology of over two decades ago when the code case was first formulated. N-47 is truly not a life prediction code, but rather a code for assessing, with a high degree of confidence, that a structural component will indeed last longer than some prescribed lifetime. The question of how much longer than the prescribed time is not addressed. The code is well suited for terrestrial structural components that do not have limitations on mass or weight. Large factors of safety are imposed on minimums of large quantities of material property data to create design curves that are highly conservative. Furthermore, the code recognizes only a limited number of engineering alloys which are currently used in the nuclear pressure vessel and piping industry. None of the Code Case N-47 alloys are candidates for use in a space-based Stirling engine.

As a general rule, one would not expect Code Case N-47 to be applied successfully to launch-weight hardware. However, the basic methodology, minus excessively large safety factors, could be employed if sufficient information were to be generated on the materials of interest. Only short-time creep, creep-rupture, creep-fatigue, and environmental attack behavior can be generated for the SSPC starfish heater head material within the time remaining before design details must be fixed. Consequently, design curves for the 60,000 hr time frame would have to be estimated using short-time data and extrapolation procedures.

Creep rate and creep-rupture characteristics measured at short times, but high temperatures, can be used to estimate behavior in the desired long-life regime at service temperatures. For thermally activated processes such as creep and creep-rupture, it is possible to interchange the role of temperature and time using methods referred to as time-temperature parameters. One of the first, and most common, is the Larson-Miller Parameter (Larson and Miller 1952). At a given stress, the numerical value of the parameter will be the same for the desired temperature and required duration as it is for a higher temperature but significantly shorter duration. The unstated assumptions associated with classical time-temperature parameters is that there are no changes in physical mechanisms of creep and rupture, there are no metallurgical structure changes (precipitation of carbides, grain growth, etc.), and that environmental interactions are unaffected. Obviously, actual conditions deviate from the ideal and resultant extrapolations suffer losses of accuracy. Factors of safety are thus imposed to cover the possibility of non-conservative inaccuracies.

A problem with time-temperature parameters is the fact that most are based upon an inflexible behavior that is extrapolated in a rigid, uncompromising way. New generations of time-temperature parameters have evolved over the past couple of decades (see for example, Manson and Ensign 1979, and Manson and Muralidharan 1983). These take advantage of the desirable features of the established parameters, but allow deviation from their rigidness. In fact, the new methods become so flexible that they can not be used as a stand-alone parameter. A minimum amount of short-time data is required to "calibrate" the parameter for extrapolation. However, the resultant extrapolation can be made with greater confidence than would be possible with a less flexible extrapolation method.

Time-temperature parameters have been used principally for creep-rupture extrapolation and occasionally for steady-state creep extrapolation. Time-temperature parameters have not been developed for other forms of structural material degradation such as fatigue, creep-fatigue interaction, or environmental degradation. Extrapolation procedures for creep-fatigue behavior are in their infancy. The time- and cycle-fraction rule as used in N-47 for creep-fatigue interaction has not been verified for lifetimes in excess of about 10,000 hr. A version of the Strainrange Partitioning method based on measurements of tensile test and long-time creep-rupture ductilities has been verified for N-47 materials for lives approaching 10,000 hr (Saltsman and Halford 1979).

STRUCTURAL ANALYSIS & VISCOPLASTIC CONSTITUTIVE MODELS

The durability of structures can be determined through prototype testing or a combination of analytic assessment and component or sub-component testing. The latter approach is more common for expensive, long-lead time structures such as the space-based Stirling engine. Analytic assessment of the durability of a structural component is accomplished by first determining the creep-fatigue-environmental durability of the materials of construction at the temperatures and times of operation. The tacit assumption is made that a component and a material characterization sample (test specimen) in the same physical and metallurgical state as the material within the component will have the same lifetime if both are subjected to the same stress-strain-temperature-time conditions in the same environment. In a material characterization sample, the imposed environment, temperature, stress, and strain can be controlled or measured as functions of time. However, in a structural component, these factors are uncontrolled and seldom measurable. Invariably, the local stresses, strains, and temperatures must be calculated using thermal and structural analysis techniques. Heat transfer analyses within thermally isotropic solids is well within the current state-of-the-art. However, gas-to-solid surface heat transfer calculations invariably require spot calibrations of measured temperatures to fix heat transfer coefficients.

Structural analyses can vary considerably in their sophistication, and may range from simple classical mechanics models of beams, plates and shells to computer-based, three-dimensional viscoplastic finite element approaches. Obviously, certain material properties and characteristics must be known before analyses can be performed. So-called "structure-insensitive properties" such as thermal conductivity, thermal expansion, Young's modulus of elasticity, and Poisson's ratio can be measured with sufficient accuracy on a similar alloy. However, the "structure-sensitive properties" such as yield strength, fatigue resistance, creep resistance, and viscoplastic characteristics must be determined on alloy samples that are more representative of component materials. Durability is governed to a large extent by the structure-sensitive properties.

Non-linear FEM computer codes have been developed to a high degree of reliability (for example, MARC, ANSYS), but suffer from high computer costs. Many computer codes can accept a wide range of viscoplastic material constitutive models (the temperature-stress-strain-time response characteristics of a material). Viscoplasticity model constants (for example, Walker 1981, Robinson and Swindeman 1982, and Freed and Walker 1990) have as yet to be evaluated for SSPC materials of interest. Obviously, it will not be possible to obtain long-time exposure properties for these materials. However, very low strain rate constitutive response behavior can be generated in the laboratory within a reasonable period of time.

Not only does the designer have to be concerned with the difficult problems brought about by the high temperatures coupled with very long lifetimes, there remains the ever present problem of dealing with multiaxiality of stresses and strains. In the finned starfish heater head design, there is a high degree of biaxial stress within the plane of the thin wall due to high internal pressures. As a general rule, material flow and failure properties are measured under axial loading. Translation of axial properties to multiaxial conditions requires use of a multiaxial stress-strain model. Numerous models are available, and range from the classical von Mises and Tresca yield criteria to the recent Lohr and Ellison (1980) and Kandil et al. (1982) parameters for multiaxial fatigue. None have been verified for long-lifetime conditions, nor have they been verified for relatively new alloys. Again, approximations will be necessary in assessing the deleterious effects of multiaxiality. Limited calibration of multiaxial flow and failure criteria from short-time multiaxial experiments would be valuable in increasing the accuracy and confidence level for assessing lifetimes under biaxial stress-strain states at long lives.

EXPERIMENTAL APPROACHES

Many of the long-lifetime prediction problems discussed above can be addressed by conducting well-thought-out experiments and making logical engineering assumptions. For instance, the question of thermal aging and its effect on long-term creep behavior can be investigated by pre-exposure testing. In these tests, the sample is thermally aged in a furnace at a temperature well above the component's operating temperature for a time that is much shorter than the design life. The sample is then loaded uniaxially to stress and temperature levels prototypical of the component's application. The philosophy behind this test is to accelerate the time-dependent thermally activated metallurgical changes associated with long-term temperature exposure. A difficulty with this test is that aging temperatures must be high enough to allow for changes in the allotted time and still be low enough not to cause other unwanted changes such as formation of precipitates and excessive grain growth. Another disadvantage is that stress-dependent dynamic strain aging phenomena can not be emulated.

Creep-rupture data are invariably generated under uniaxial loading conditions and cannot, by themselves, represent more general multiaxial material behavior. To aid in understanding the multiaxial aspects of the design and material behavior, sub-component testing is needed. There are two approaches that can be taken in sub-component testing. The first is to test complex-shaped components using specialized test systems. This approach is expensive, and interpretation of the results is difficult. The alternative approach utilizes specimens that are simple geometric representations of the component in question. For the starfish heater head, a thin-walled tube can be pressurized and loaded axially, producing an multiaxial stress state approximating the conditions that the material would experience during standard operation of the SSPC. Advantages of this test include the ease of monitoring material response and the fact that it is more representative of the actual component than a uniaxial test would be. However, the test equipment is still quite sophisticated and expensive.

The above experimental inadequacies are related to creep-rupture testing. However, many of these same arguments are also true for fatigue, creep-fatigue, and environmentally dominated tests. The applied load histories for all these tests are very idealized and are seldom representative of a component's operational loads. Furthermore, the load levels of these tests are typically larger (and hence lower lives result) than the projected levels of the starfish heater head. An approach to investigate the effects of actual load histories is to apply mission simulation mechanical and temperature histories onto a test sample and observe the material response. This method was used by Ellis et al. (1987) in a similar low stress-high temperature situation. By imposing prototypical load histories, the material experienced creep-ratchetting which would lead to a eventual component failure. Since in many cases the stress-strain-temperature histories are unknown, this method requires FEM analysis to provide this information.

The experimental approaches mentioned herein will provide valuable insight and guidance towards a design that would survive the proposed mission life of the SSPC.

CONCLUDING REMARKS

The various tools available for assessing long-lifetime durability have been discussed. At the present time there are only a limited number of approaches that can be used to predict long-life creep, fatigue, and environmental attack. Each will require calibration and short-time verification for the specific materials of interest to gain confidence in their use. The SSPC design schedule precludes development of long-term durability tools; nevertheless, developments must begin for future long-range NASA missions.*

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