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13. ABSTRACT (Maximum 200 words) A versatile test facility is described for the measurement of tensile, compressive, fracture toughness, mechanical fatigue, and thermomechanical fatigue properties of metals, intermetallics, ceramics, and composites at 25 to 2000 °C in vacuum, inert, and reducing atmospheres. The test system consists of a fully automated computer controlled axial load frame; a test chamber designed for interchangeable heating elements for different environments, grips for different types of loading and thermal histories, and ceramic rod extensometry. The facility overcomes a serious deficiency in test facilities and procedures to obtain material property data for the design of components subjected to high cycle fatigue loading conditions, thermomechanical fatigue, fatigue crack propagation in controlled atmospheres. The instrumentation fills the need to provide the designers with reliable and reproducible mechanical property data obtained under simulated loading conditions and operational environments. Damage tolerance concepts and predictive models that accurately reflect the combined effects of loading conditions and environmental species can be developed for qualification of mature and emerging high temperature materials for hypersonic/high speed vehicle structures and advanced aircraft engines.			
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**HIGH TEMPERATURE ENVIRONMENTAL TEST FACILITY FOR UNIAXIAL
TESTING UNDER CYCLIC LOADING**

FINAL TECHNICAL REPORT

Grant No. F49620-95-1-04 70

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INTRODUCTION

A versatile test facility is described for the measurement of tensile, compressive, fracture toughness, mechanical fatigue, and thermomechanical fatigue properties of metals, intermetallics, ceramics, and composites at 25 to 2000 °C in vacuum, inert, and reducing atmospheres. The test system consists of a fully automated computer controlled axial load frame; a test chamber designed for interchangeable heating elements for different environments, grips for different types of loading and thermal histories, and ceramic rod extensometry.

The facility is being used for experimental evaluation of mechanical properties that characterize the behavior of conventional and emerging materials for aerospace structures under a broad range of conditions representative of those encountered in service. The instrumentation is a key element in the development of (1) relationships between the microscopic structure and the macroscopic structural response of high temperature materials in inert and aggressive environments, (2) unique combined thermal, environmental, and mechanical testing methodology now possible with modern instrumentation, and (3) testing methodology for low ductility intermetallics.

The facility overcomes a serious deficiency in test facilities and procedures to obtain material property data for the design of components subjected to high cycle fatigue loading conditions, thermomechanical fatigue, fatigue crack propagation in controlled atmospheres. The instrumentation fills the need to provide the designers with reliable and reproducible mechanical property data obtained under simulated loading conditions and operational environments. Damage tolerance concepts and predictive models that accurately reflect the combined effects of loading conditions and environmental species can be developed for qualification of mature and emerging high temperature materials for hypersonic/high speed vehicle structures and advanced aircraft engines.

Our group at Washington University has active research programs in the synthesis, processing, and characterization of advanced high performance structural and functional materials, which require state-of-the-art mechanical property measurements. Washington University, MTS and MRF have designed and built a high frequency - high temperature - environmental fatigue system under AFOSR Grant No. F49620-95-1-04 70. This report describes the system and the research projects in which the equipment is being used.

Significant interest has developed recently in high cycle fatigue testing of aircraft engine structural materials. This has been driven by the US Air Force, which is in search of new methodologies for life prediction and design against high cycle fatigue failure. Typically, fatigue problems emanate from a damage site, such as a compressor blade that has been damaged. Fatigue failure occurs when these damaged sites lead to crack propagation, driven by vibration stresses, at high mean stresses but low stress amplitudes. Since the vibration frequencies are high and the stress amplitudes are low, data is scarce. Fatigue lifetimes of up to one billion cycles are of interest. These lifetimes are difficult to attain in standard testing machines at normal testing frequency on the order of 10 Hz. The High Cycle Fatigue machine described herein is capable of operating at frequencies of 1000 Hz or two orders of magnitude greater than many conventional machines. Obtaining fatigue life data in the one billion-cycle regime is now possible. In response to these

needs, and in order to study frequency effects, a new type of servohydraulic machine has been developed. At this time the machine has been installed and used to gather high cycle fatigue data on 7075 aluminum.

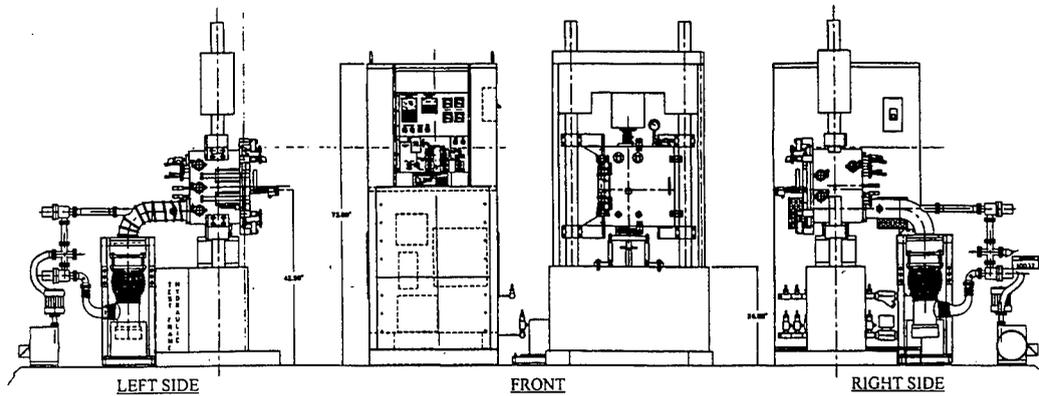
DESCRIPTION OF THE HIGH CYCLE FATIGUE SYSTEM

The HCF system is capable of applying cyclic tension and compression at positive and negative R ratios at loads up to 2000 pounds, frequencies up to 1000 Hz and temperatures up to 2000 °C in a vacuum or process gas environment. The current specimen grips are rated for a maximum temperature of 1000 °C and the extensometer is rated for 1200 °C. The system is capable of fatigue testing conventional aluminum and titanium materials and high temperature or single crystal or poly crystalline Ni based super-alloys under high cycle fatigue at high R ratios at temperature in a vacuum or in Ar, N₂, He and Ar or N₂ with 7% H₂ at 2 psig. The system, Figure 1, was installed at Washington University on September 15, 1997. An industrial acoustic enclosure, Figures 2 and 3, was installed by Washington University to contain the acoustic noise generated by the system.

Fatigue System

The system consists of a unique frame and a high performance, high flow voice coil servo-valve. The concept behind this combination of servo-valve and frame type is to design a high frequency system capable of achieving significant actuator displacements at 1000 Hz. To meet these requirements, the frame is designed with a reduced height baseplate to minimize deflection and increase stiffness to improve dynamic performance. The column height is reduced to reduce high frequency resonant effects. A tie bar across the top of the columns is added for stability. The crosshead is manufactured to close tolerances to increase stiffness and achieve better alignment. The seal-less actuator is ceramic coated to alleviate potential deterioration of the surface of the piston rod due to seal contact. The present system is designed as a high frequency system for fatigue and fracture of metals in a vacuum and/or at high temperature. The 40 gpm voice coil valve is selected for several reasons. One consideration is the superior high response and high flow characteristics, which are crucial to achieving larger actuator displacements at high frequencies. Valve life is also a factor. The voice coil valve is a longer life valve than those of the tradition nozzle flapper design.

The servovalve used in the system is a "voice coil" servovalve, Figure 4. The voice coil valve uses an electrodynamic pilot stage, driven in the same way as an audio speaker. The voice coil moves a spool in the pilot stage, such that hydraulic fluid from the pilot stage is used to drive the spool in the main stage. The main stage is a hydraulic amplifier of the pilot stage. There is no torque tube or flapper as in a conventional servovalve, and the only parts that are stressed are the coil springs in the pilot stage. In addition to the expected increase in durability, the voice coil valve has superior high frequency response and higher flow rates, characteristics which are both crucial to achieving larger actuator displacements at very high frequencies.



Washington University HCF System with Vacuum / Process Gas Chamber (10/30/97)

Figure 1. Schematic diagram of high cycle fatigue environmental system.

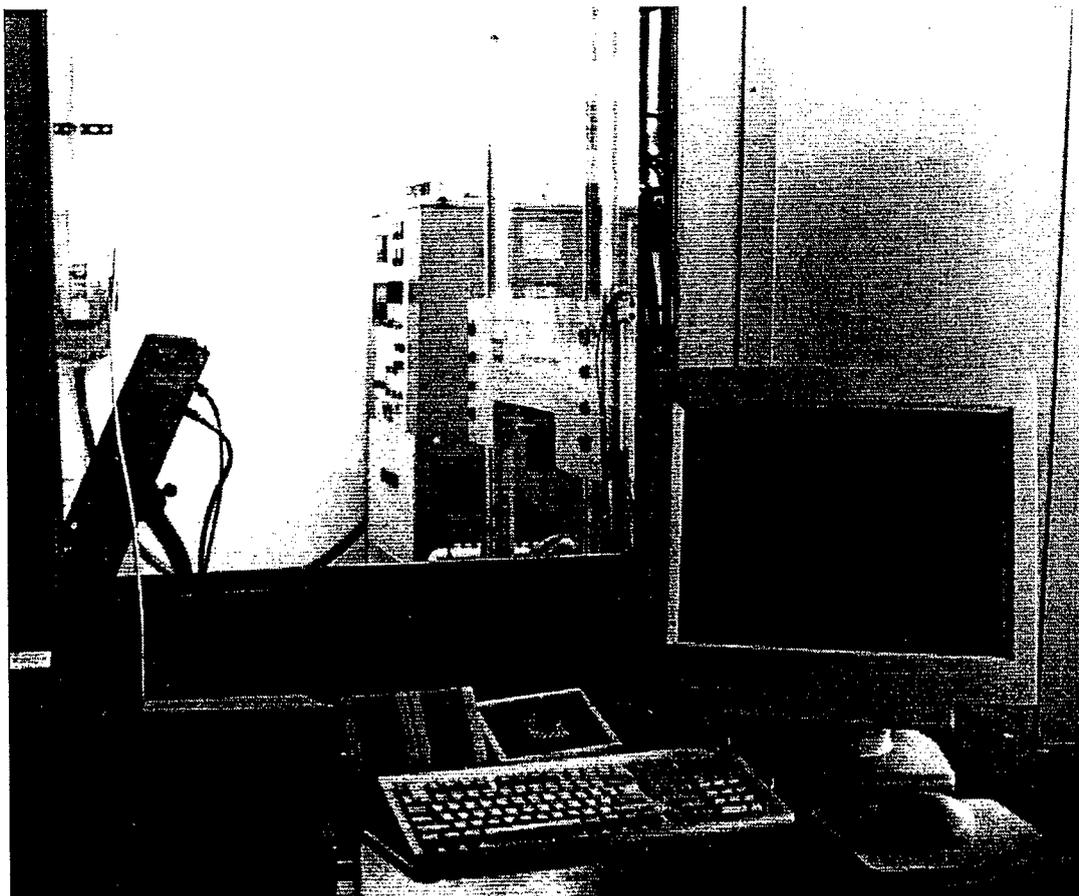


Figure 2. Acoustic enclosure and control console of the High Cycle Fatigue System.

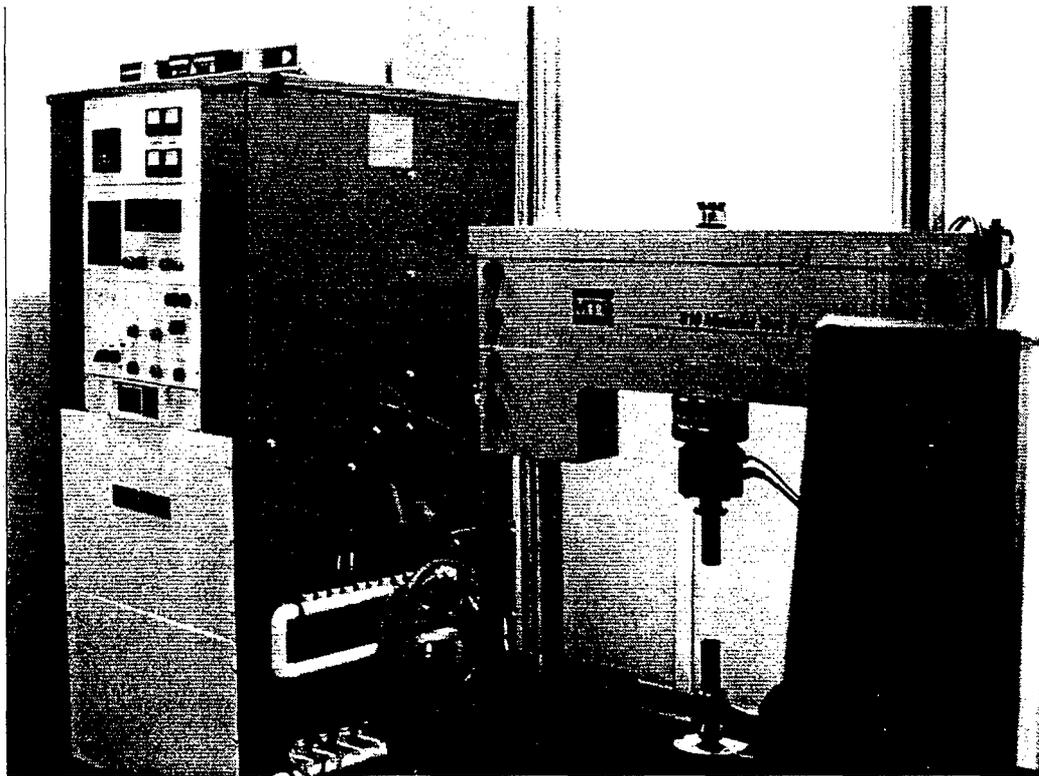


Figure 3. Interior of sound enclosure showing the vacuum and power controller on the left and the load frame on the right.

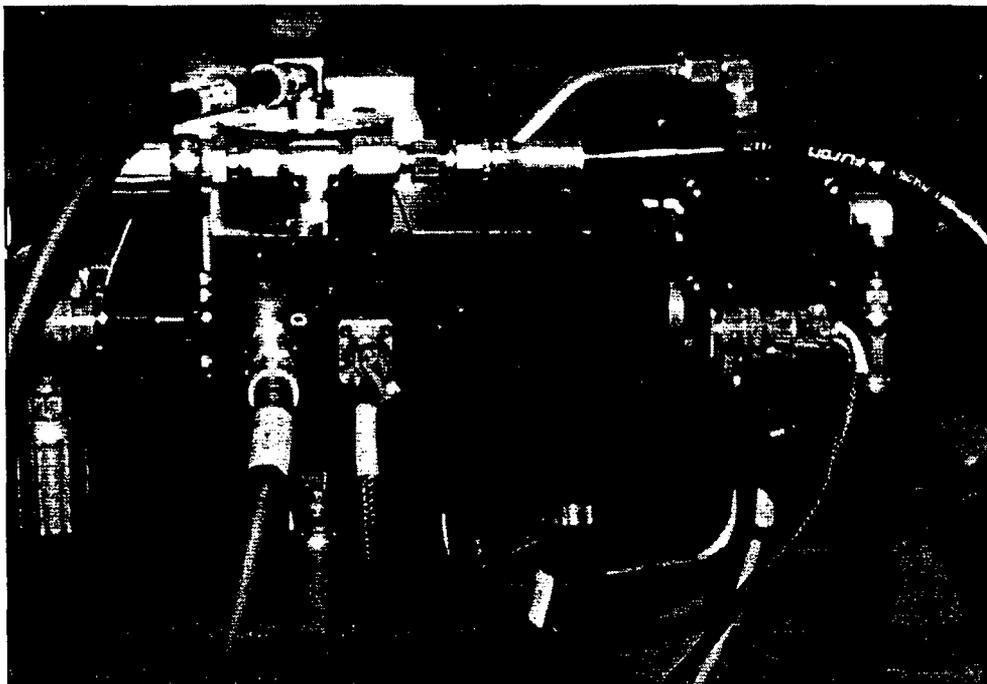


Figure 4. The voice coil three stage servo valve.

System Controller

The digital system which controls traditional servohydraulics also controls the HCF system; the only modifications are the acceleration compensation, and the use of an adaptive control scheme which yields steady-state load control at 1000 Hz. The digital controller utilizes a phase amplitude compensator (PAC) to detect and correct amplitude roll-off and phase lag in sinusoidal command waveforms. The TestStar II controller provides multi channel control for advanced applications such as thermal mechanical fatigue and simulation. The controller features include additional control, data acquisition, and input/output capabilities over the single channel systems. TestStar II has an intuitive user interface, which makes it suited for demanding applications.

TestStar II is an automated digital control system used to control closed loop servo hydraulic testing systems with up to four servo-loops. TestStar uses graphical, mouse driven system software to set up and manage tests, and collect data. Time-critical processes such as closed loop control, limit detection and data acquisition take place in the controller firmware. TestStar II can be configured on dynamic test systems. One TestStar chassis can control up to four channels simultaneously. This feature makes TestStar ideal for complex testing such as thermal mechanical fatigue. The TestStar II controller system includes three major functional elements: (1) TestStar II system software operating on a personal computer with Windows/NT. (2) Real-time firmware functions operating inside the TestStar II's digital controller chassis. and (3) A load unit control panel provides the capability to manually control hydraulic fluid power and actuator position. In addition to the basic controller elements, application software is available to provide test capabilities for a variety of applications. TestWare-SX is a flexible multi-purpose software application used to create and run tests. Through a series of software windows, tests are designed in a systematic manner, with test system function generation and data acquisition requirements defined for each part of the test. Automatically triggered limit detectors, and custom designed operator-triggered event detectors are configured through TestWare-SX. Command signals for external devices, such as temperature controllers can be generated. Test data are stored in a standard text format for post-test analysis. Enhancements to TestWare-SX include run-time plotting, advanced function generation, high speed data acquisition, data monitoring for trends, and run time ramp control for incremental stepping toward indeterminate end levels. Other application software packages such as Low Cycle Fatigue, High Cycle Fatigue, Fatigue Crack Growth, Fracture Toughness, and TestWorks for Static Applications are available.

A personal computer user interface replaces hardware knobs and buttons, reducing operator errors. In addition, an optional manual actuator positioning control protects the specimen and speeds testing. A selection of pre-configured test system detector actions can be set up. On triggering a limit, error or under-peak, actions are implemented by microprocessors located inside the TestStar chassis for the fastest response to save valuable specimens or prevent test equipment damage. Customized controlled shutdown sequence can be implemented, which can be particularly valuable in protecting complex and expensive specimens. Multitasking software allows simultaneous viewing and adjustment of on-screen data read-outs, tuning controls, operator event triggers, run-time plots and run-time rate controls while the test is in progress. Manually operated actuator positioning control protects the specimen and speeds testing. The actuator positioning control operates in a load-limited stroke mode to rapidly position the actuator while keeping the force applied to within the pre-set limit. Multitasking allows analysis data, generation of reports, or

network operations on the PC while a test is running. TestStar II can store and retrieve an unlimited number of user-defined system and test set-ups. Flexible signal conditioning and external signal input capability allows other transducers and signal conditioners. Data can be collected from sensors conditioned by existing amplifiers. In addition, on-board TestStar signal conditioners accept signals from almost any transducers such as bonded strain gages for measurement or control. TestStar II provides a convenient built-in bridge completion resistor feature that simplifies working with strain gages, of particular interest when multiple gages may be used for specimen damage monitoring.

The basic TestStar chassis has 13 available slots for signal conditioners in a single servo-loop configuration, as well as inputs for up to eight externally conditioned high-level sensor signals. Auto tuning quickly and reliably sets up PID parameters. Control mode switches can be made between any internally or externally conditioned sensor or calculated signal. Firmware in the controller-resident high-speed processors is initialized by the TestStar II system software. New controller capabilities are provided by system software updates that include new processor firmware. Data acquisition processes are easy to set up. Timed, peak-valley, and level crossing can collect data on all channels at up to 5 kHz sampling rate. Data is buffered (using one of several buffering options) before they are sent to disk. Thus avoiding excessive data collection, saving disk space and making post-test analysis much easier. Transient test events are accurately captured. Data skew between channels is eliminated for more accurate post-test analysis. Simultaneous sample and hold data acquisition for all data acquisition channels eliminates phase shifting of data between large numbers of channels, allowing simplified post-test phase angle measurement and much easier data analysis, including material damping calculations. A high-speed controller resident data acquisition option allows single channel acquisition rates of 50 kHz.

Fast and accurate calculations are made inside the TestStar chassis. Microprocessors used for calculations are fully integrated with other high-speed controller processors inside the TestStar chassis for real-time calculated signal control, limit detection and data acquisition. Calculated variable control tests are easy to set up, without complicated programming. Equations are typed into system software, combining sensor signals in the desired way for control feedback. Minimum and maximum values expected for the calculated parameter, determined by the user, are entered for limit detection. Calculation constants, for simplification of repeated mathematical operations, can be user-defined. Up to 8 calculated signals can be created using built-in linear, trigonometric, exponential or logarithmic math functions by combining any internal, calculated, or externally connected sensor signals, for new test capabilities such as post failure test control with calculated feedback. Calculations are made in firmware at the closed loop update rate. True stress and strain, energy, and averaged value of multiple sensors are examples of the calculated control mode possibilities. This feature includes high-speed circular buffers that store the previous 100 data points from any connected sensor or calculated signal. For example, stored displacement and time data can be used to define strain rate signals. Calculated inputs can be a tool for event or limit detection. A calculated parameter can be continuously monitored and used to trigger a control mode switch, a new test sequence or emergency shutdown. For example, real time elastic modulus can be calculated using buffered strain and load data. This signal can be monitored to detect specimen stiffness change, and upon triggering an event detector, used to terminate a test.

Phase Amplitude Control (PAC) gives requested end levels and phase relationships. PAC matches the requested sine wave form phase and amplitude to the phase and amplitude achieved by the test system. Where phase angle measurement is critical, PAC provides known phase relationships between command and feedback signals, allowing easy determination of material damping properties. It also broadens the effective frequency bandwidth of the test system. Spectrum Amplitude Control (SAC) assures that requested end levels are achieved. A command compensation file is generated by SAC that's used to continuously adjust the control system command signal for more accurate testing. It's used during file playback of non-repeating, synthetically generated or recorded loads such as flight spectrum, vehicle or machinery vibrations. Frequency-based Iterative Technique (FIT) provides both amplitude and wave shape assurance. Fidelity of repeated non-standard waveforms such as haversine pulse or other user-defined arbitrary wave shapes is improved. Cascade control gives more feedback transducer selection choices. When a feedback signal is erratic, rapidly changing or unreliable, an inner/outer loop control strategy helps keep the system under control when simple PID controllers cannot. Feed-forward helps the control system respond accurately during high performance testing. TestStar uses a PIDF (Feed-forward) servo loop closure algorithm and provides full operator adjustment capability of all tuning parameters. This enhancement of simpler PID control systems improves system response when testing soft and non-linear materials in load control.

Grips

The system has axial grips that are capable of fully reversed loading and high temperature testing, Figure 5. The two design constraints on grips and fixtures are that the mass of the grips be minimized for optimum system response; and the length of the fixtures be short, to minimize load frame motion and resonance. The axial grips are designed for conventional ASTM button end fatigue specimen and are fabricated from a high temperature alloy to operate at temperatures up to 1000 °C.

Dynamic Load Calibration

Acceleration effects due to the moving mass of the load frame can be significant at high frequencies and are compensated for in the control loop. The method of doing so utilizes an accelerometer positioned on the active elements of the load cell. The calibration method is dynamic load verification with a strain-gauged specimen in the load frame, Figure 6. The specimen strains are statically calibrated using the system load cell. As the specimen is loaded at the operating frequency, the difference between the system load cell and the specimen strain is monitored, Figure 7. The acceleration compensation circuit automatically adjusts the system until the difference between the two signals is nulled.

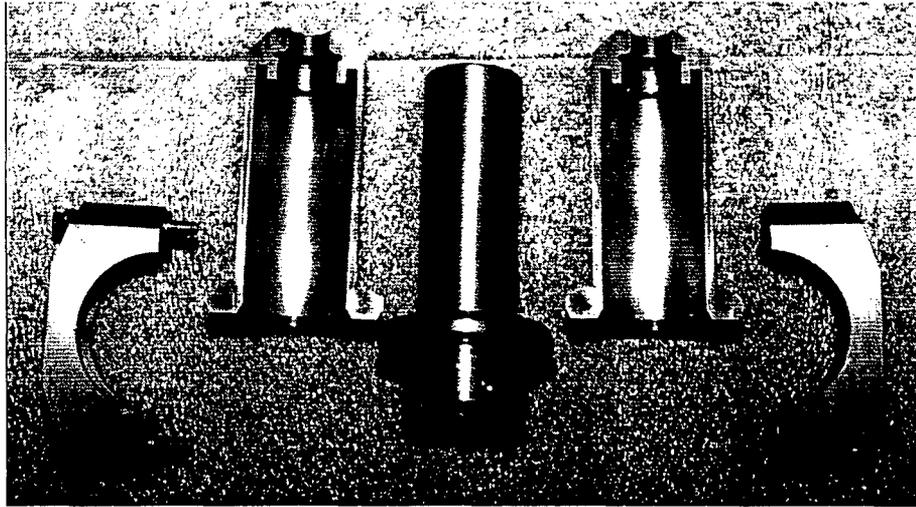


Figure 5. High temperature tension compression grips for ASTM button end specimens.

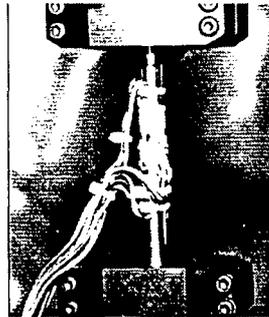


Figure 6. Strain gaged alignment specimen.

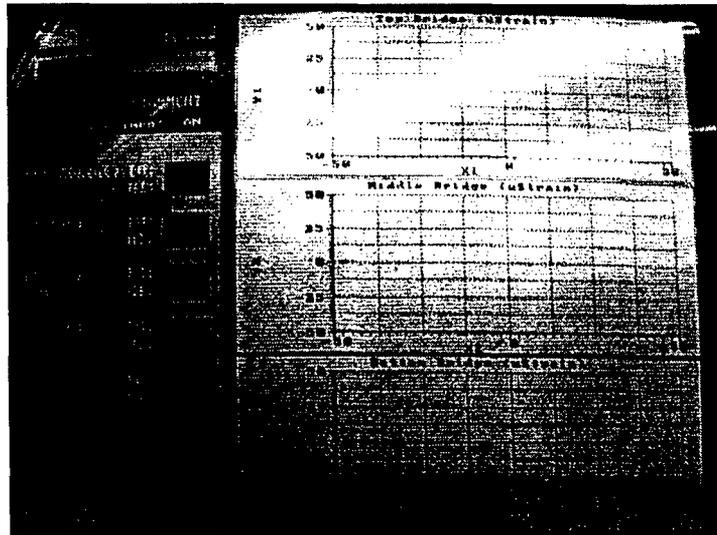


Figure 7. Computer display of alignment data.

Chamber

The furnace is a Front Loading, Physical Testing Furnace, with a usable work zone of 3.5" dia. x 3.0" high, and a maximum operating temperature of 2000 °C. The furnace chamber, Figures 8 and 9, has the following features:

- Rectangular double walled water-cooled 304L stainless steel.

- Polished to a #4 finish on the inside and outside surfaces.

- Electropolished after all machining and welding, to clean all surfaces thoroughly.

- Ports to accommodate the temperature thermocouples, vacuum sensors, vacuum system, water feed-through for the extensometer, RGA, blanked off port for electrical feed-through, Left hand hinged front opening door.

- 1/2" dia. rotating sight window on the front door, centered to the hot zone.

- The hot zone is a 180" split design, with Tungsten/molybdenum shields and tungsten mesh heating element.

- There are four water-cooled copper power feed through, which supply power to the element.

- The chamber is large enough to house extensometer and includes extensometer mounting brackets.

Physical Test Kit

- Two tension/compression cold rods, these rods are water-cooled centerless ground 440 stainless steel hardened to Rc60.

- Top stainless steel welded bellows for alignment, this assembly also seals the top water-cooled rod by an o-ring seal.

- Bottom stainless steel welded bellows for alignment.

- Lower double Lip Seal housing assembly, this assembly seals the lower cold rod to allow it to oscillate with a frequency of up to 1000 Hz.

Vacuum System

Vacuum system performance is capable of 10^{-5} TORR vacuum range in high vacuum mode. The high vacuum pumping system, Figure 10, consists of the following:

- Varian VHS-Diffusion pump.

- VRC electro-pneumatic high vacuum gate angle valve.

- Varian cold trap (baffle), cooled with a non-CFC refrigerant.

- An electro-pneumatic diffusion pump foreline and chamber roughing valves.

- A rotary vane dual stage mechanical pump with exhaust filter.

- All stainless steel manifold to connect these component together.

- Varian senTORR Cold Cathode Gauge controller with associated vacuum sensors.

- Graphic display panel with switches for operating the vacuum system.

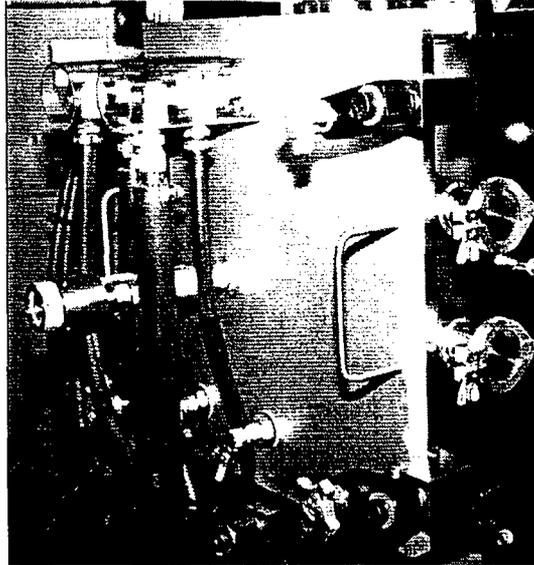


Figure 8. Front of the environmental chamber showing sight glass and power cables.

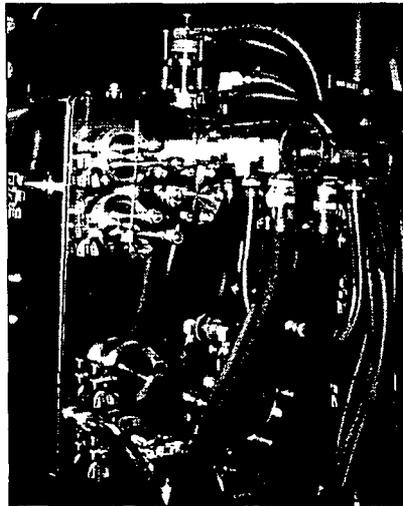


Figure 9. Back of the environmental chamber showing ports and power cables.

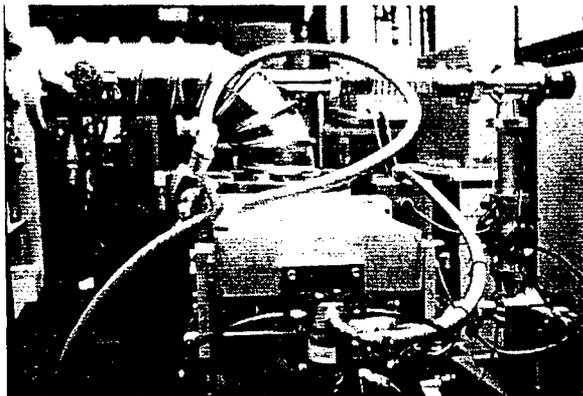


Figure 10. Vacuum system diffusion pump.

Process Gas System

The gas system performance is 2 psig maximum pressure (Ar, N, He and Ar or N with a maximum of 7% H.

- A solenoid operated gas inlet valve.
- A gas Flowmeter with flow control valve.
- A 2 psig factory set relief valve.
- A compound gauge (30" Hg. x 30 psig).

Cooling System

The water cooling system is designed to cool all components to 150 °F and includes the following:

- Water strainer on the inlet manifold
- An inlet manifold with a number of circuits to cool all components sufficiently.
- All hoses necessary to connect the components to the manifold.
- A ball valve on each circuit of the drain manifold.
- Water flow system interlock switch on the main drain.

Power Supply

The power supply is designed to accommodate an operating temperature of 2000 °C.

- A main circuit breaker is used as a main power disconnect and over current protection.
- A contactor which turns power onto the element or to disconnect power because of interlock.
- An SCR which modulates the power to the elements in a reliable and accurate fashion.
- A three phase to two-phase main step-down transformer.
- Two volt and two ammeters to monitor the power the furnace is using.
- Water-cooled power cables in order to carry the high current and provide cooling for the copper power feed through.
- An auxiliary control transformer.
- Hot zone power on and off pushbuttons.

Temperature Control

- Honeywell temperature programmer / controller. The input to this instrument is a Type "C" thermocouple with a range of 0-2000 °C.
- Honeywell hi-limit controller. The input to this instrument is a type "C" thermocouple.
- Varian vacuum gauge controller to control the operation of the high-vacuum system.
- Allen-Bradley Controller to control all the logic inherent to the furnace operation.

RESEARCH PROJECTS USING THE HCF SYSTEM

Aircraft Structural Alloys

A robust high cycle fatigue analysis method must be able to correlate the data generated from all four test methods: axial constant amplitude, beam bending constant amplitude, axial random and beam bending narrow band random. For example, the methodology must be able to use constant amplitude data to predict the fatigue life of beams exposed to random loads in bending. The following tasks will be used to systematically develop this correlation procedure. A literature review of available high cycle fatigue test data will be completed for selected alloys. This will cover axial tension, rotating beam, and vibrating beam fatigue data. The data will include da/dN versus ΔK crack growth data and strain-life data. Both sets of data are needed for correlating strain-life crack initiation predictions with crack growth based analysis. A significant database exists at Boeing - St. Louis from previous combined buffet/maneuver load and acoustic fatigue studies.

Supplement the available data with a series of high frequency tests in constant amplitude using the Washington University facility. The tests will be completed at room temperature and at elevated temperature. This will include generating da/dN versus ΔK crack growth curves and strain-life data. The da/dN data generation will focus on defining the lower part of the curve below 10^{-7} inch/cycle in order to verify threshold stress intensity factors for large cracks. Part of the task will evaluate short crack behavior and its effect on the lower part of the da/dN curve. Use the available and generated constant amplitude data to predict the fatigue life of beam specimens tested under random bending and random axial vibration loads. Crack growth based analysis using fracture mechanics and equivalent initial flaw sizes will be used to correlate the constant amplitude beam bending and axial fatigue test data. Equivalent initial flaw sizes determined from this analysis will be compared with the size of metallurgical flaws from which the cracks are found to develop to determine if a physical correlation can be established. The fracture mechanics analysis will use available crack growth retardation models coupled with short crack analysis methodology.

Using the results of the correlation between axial and bending fatigue tests, use constant amplitude bending fatigue test data to predict axial, variable amplitude, spectrum fatigue failures. Verify the predictions by testing a series of axial test coupons under variable amplitude, spectrum fatigue at Washington University. Comparisons will also be made with other available beam random fatigue test data. This project was initiated on January 1, 1998 to study 7075 and 7050 aluminum alloys for the Boeing Company.

IMPACT OF THE HCF SYSTEM AND FUTURE RESEARCH

We describe below how the proposed HCF environmental test facility will establish new research capabilities and open new research areas that are potentially relevant to DOD areas of interest.

Hypersonic/High Speed Vehicles

Advanced aerospace vehicles are placing demands on materials never before encountered. The materials must be capable of long-term operation in often severe thermal, mechanical, and chemical

service environments. A fully reusable, hot-structure vehicle will see thermal environments ranging from cryogenic up to the maximum useful operating temperature of its materials; mechanical environments combining high pressure, severe thermal, and extreme acoustic loads; and chemical environments consisting of oxygen, hydrogen, and hydrogen rich water mixtures over a wide range of temperatures and pressures. Although successful control of the effects of most oxidizing environments is well understood, the breadth of experience and understanding that exists for the reducing environments of hydrogen and hydrogen rich water, particularly in hot structures is still a major materials challenge in hypersonic vehicle technology.

The susceptibility of a specific metallic structure to hydrogen embrittlement will depend on three primary factors: (1) the possible hydrogen interactions with the structural material, (2) the ease of hydrogen transport into the structural material, and (3) the specific form of degradation. The following four distinctly different hydrogen interactions are capable of changing the behavior of the metal in some way. (1) Interaction of hydrogen with the electronic structure and consequent reduction in the bond strength of the metal thus facilitating separation of the metal along crystallographic planes, (2) Interaction of hydrogen atoms with dislocations leading to changes in plastic deformation characteristics, (3) Reaction of hydrogen with itself or with another chemical species to form a gas-phase reaction product which may precipitate at voids and interfaces, and (4) Hydride formation when solid-solution limit is exceeded. These interactions become increasingly dominant with extended low and high temperature exposures, numerous and relatively rapid thermal cycles, severe thermal gradients, and high static and dynamic loading leading to degradation in mechanical integrity and performance of structural components.

If a structure is fatigue-critical, the effects of hydrogen on fatigue crack initiation and fatigue crack growth will play a significant role in determining the life of the structure. The use of materials exhibiting good thermal/mechanical behavior is critical to the success of any hot-structure aerospace vehicle. Many lightweight materials such as titanium aluminides, metal matrix composites, carbon-carbon composites, and ceramic matrix composites are attractive candidates for such hot-structure aerospace vehicles. However, our present understanding does not permit the reliable use of most of the above types of materials on hypersonic vehicles where a hydrogen environment may exist. Recent NASP sponsored programs have addressed some aspects of hydrogen-material interactions. For example, exhaustive studies have been conducted on the effects of hydrogen on microstructural changes and room temperature mechanical properties such as strength, ductility, and fracture toughness. However very little is known regarding the effects of internal and external hydrogen on high temperature properties such as creep, fatigue, fatigue crack growth rates, and thermomechanical fatigue life. This situation is partly because of the lack of adequate facilities for such studies. We plan to use the proposed test facility for a systematic study of the effects of internal and external hydrogen on microstructural and mechanical properties modifications of several high temperature materials intended for use in hypersonic applications.

We have recently completed a comprehensive study of the effects of internal and external hydrogen on microstructural modifications, creep, ductile-brittle transition temperature, and tensile properties of several conventional titanium alloys, alpha2 and gamma titanium aluminides, Mo-Re, Haynes 188, and NARloy Z. Contrary to the general belief of incompatibility of titanium alloys with hydrogen atmosphere, several of the titanium aluminide/microstructure combinations exposed to hydrogen atmosphere maintain attractive combinations of strength and ductility. If the alloys are

ranked using the criteria that the hydrogen charged samples maintain a plastic ductility of at least 1.5%, and the hydrogen charged samples withstand a stress equal to 80% of the stress withstood by the uncharged sample. Several of the titanium aluminide /microstructure combinations satisfy the above criteria. Whereas significant progress has been made in identifying the effects of hydrogen on tensile and creep properties of candidate materials for hypersonic vehicles, the hydrogen effects on damage critical properties have remained conjectural and unsettled. The test facility described in this report will significantly enhance our capabilities to provide answers in a timely manner to designers of hypersonic vehicles.

Integrated High Performance Turbine Engine Technology (IHPTET)

The basic IHPTET goals are to identify single- and dual-rotor engine concepts that have a thrust-to-weight ratio at twice the current levels and to demonstrate the required material/structural and component aerodynamic technologies on a timely basis for validation in the advanced turbine engine gas generator (ATEGG) and joint technology demonstrator engine (JTDE) programs. This initiative emphasizes the development of low density, high temperature, and high strength materials for IHPTET applications to achieve the aggressive thrust-to-weight goals. Many advanced materials such as titanium aluminides, titanium matrix composites, and refractory metal silicides are generally recognized as materials with low density, high specific strength and stiffness, and high service temperature capability; however their structural use has been restricted due to limited understanding of their response to service type conditions. There is an urgent need to develop database and gain a sound understanding of the high temperature damage tolerant properties of these materials. It is clear that an efficient implementation of new material and design concepts in advanced gas turbine engines requires a close interaction between the metallurgical and mechanics disciplines. The HCF facility specifically utilizes this important interaction in addressing the fatigue and fracture behavior of advanced high temperature materials.

The advanced titanium based materials for IHPTET applications must be able to operate at temperatures between 600- 1000 °C. Possible candidate materials which may potentially operate in this window include monolithic alpha 2 or orthorhombic based titanium aluminides at 600-800 °C, and gamma based titanium aluminides at 700-900 °C and continuous and discontinuous reinforced titanium aluminide intermetallic composite alloys at 700-1000 °C. For still higher temperatures, nickel aluminides, refractory metal aluminides and silicides and ceramic matrix composites are being considered. Most of the above types of materials have low ductilities and the experience and expertise of high temperature testing of low ductility materials are indeed very limited. Although a vast amount of data is available on the tensile and creep properties of these advanced materials at room and elevated temperatures, data on fatigue, thermomechanical fatigue, fatigue crack growth of these materials is very sparse and our understanding of the damage tolerant properties of these materials is very limited.

The principal variables, which affect the service life of a structural component, and the material properties required for predicting the component life, depend on the load, time, temperature, and environmental history of the components. A typical loading spectrum for a turbine engine disk is composed of a mix of high- and low-stress fatigue cycles and various periods of sustained loading. Typical fatigue cycles generally have a frequency of 0.1 Hz or lower, and are of the order of minutes. At high temperatures, crack propagation produced by mission loading is quite complex

and therefore requires the capability to predict the effects of fatigue, and creep and their interactions.

Available data on failure behavior of composites suggests that conventional damage tolerance concepts developed for monolithic metals may not be applicable for composites. Unlike most metals, composites do not necessarily fail from the cyclic or time-dependent progression of a single dominant flaw or crack. Depending on the loading conditions and architecture, composite materials can fail from the formation and growth of many cracks, which grow in various directions and orientations with respect to the reinforcing fibers and loading axes. Under these conditions, the multiple cracks constitute a damage zone that interrupts the tensile integrity of the material. Under repeated loading, this damage zone can intensify and grow until the material can no longer carry the applied loads, thereby causing failure.

The complex inter-relationships between the multitude of factors that can contribute to failure in composite structures and a review of existing literature clearly indicates a need for a systematic experimental research program to develop methodologies for the diagnosis, prediction, and prevention of failure in composite structures. The HCF facility will address issues relating to damage tolerance design concepts for composites applications in high temperature structural components. Specifically testing methods will be developed to predict the mode and rate of damage accumulation and growth and quantify the state of initial or service-induced damage. The modes of damage accumulation for composite specimens under monotonic, mechanical fatigue, thermal fatigue, thermomechanical fatigue, creep, and creep-fatigue conditions must be determined experimentally.

Thermomechanical Fatigue

Materials in gas-turbine engines are subjected to both thermal and fatigue environments where the temperature and stress/strain conditions are constantly changing. This thermal fatigue environment is often more damaging than the isothermal environment and when life prediction is based only on the latter test data, it may prove to be nonconservative. Fatigue response under thermal-fatigue environment can be quite different from that expected from the isothermal-fatigue environment. Thus, gas-turbine-engine conditions are best simulated by fatigue testing capable of imposing simultaneous, independently controlled temperature and strain (or stress) cycles, or thermal-mechanical fatigue tests. Various types of TMF tests have been used to evaluate the fatigue behavior of engine alloys under the dynamic influence of both temperature and strain (or stress). Among TMF test methods that have been applied to engine alloys are the "Dogleg" TMF test, in-phase and out-of-phase TMF tests, and "Faithful" cycle TMF test. In these TMF tests, specimens are fatigued between two significantly different temperatures. Higher temperature is generally selected to promote particular creep or environment process, while lower temperature is selected to minimize these time-dependent processes. Parameters that are expected to significantly influence the TMF response include environment, mean and range of temperature, and mean and range of fatigue strain (or stress).

Thus, mechanical fatigue resistance of materials is a limiting factor in structural components of high performance aircraft. Knowledge of thermo-mechanical fatigue damage accumulation, crack

growth and fatigue life modeling is crucial to the development of sound design methodologies for modern materials.

Fatigue behavior is extremely complicated at high temperature because of the complex interaction of thermally activated time dependent processes. These processes can usually be ignored at room temperature for some materials but must be considered at high temperature. Environmental, creep, relaxation and metallurgical factors interact with mechanical fatigue mechanisms at high temperatures. Oxide layers and microstructural changes shorten high temperature crack initiation life. High temperature also accelerates crack propagation rates.

The research in this effort is directed towards building the technology base needed to use metal matrix composites in structures. This technology base includes: characterization and evaluation of metal matrix materials (especially time dependent properties), modeling of constituent components on a micro-scale to predict properties on the macro-scale, development of the modeling necessary to determine structural integrity and durability, and structural analysis methods for reliability to provide a tool for materials selection in the design process. A laboratory database and structural analysis technology are necessary to give the designer confidence in metal matrix materials as candidate materials for structures. Life prediction and high temperature test methods must simulate real operating environments.

Research topics in thermo-mechanical fatigue which could be investigated under this effort include: mapping the failure and damage accumulation process, mechanisms of microcracking, strength and mechanisms of interfacial cracking, debonding and pull out; micro-mechanical modeling and constitutive modeling; life prediction methods which account for thermal and load histories typical of service conditions; crack nucleation and crack growth, damage mechanisms and modeling; experimental mechanics, the development of testing methods which simulate service conditions and the development of a material property data base; environmental and creep effects; microstructural changes during thermo-mechanical fatigue.

Impact of the HCF Facility on Training of Future Scientists and Engineers

The Washington University program meets a vital national need to train graduate professionals in materials science and engineering by linking current graduate programs to form a cross-disciplinary program that adds significant breadth to graduate training in materials science and engineering and fosters communication and collaborative research among engineers, chemists and physicists. At Washington University, an interdisciplinary approach to materials science and engineering is promoted by graduate curricula in materials that will train chemists, engineers, materials scientists, and physicists with much greater breadth than is provided by existing graduate programs. The graduate curriculum has been designed to span the key areas of synthesis, processing, characterization and applications in materials science and engineering. Our idea is to enhance the training that a student receives in a fundamental discipline by systematic exposure to the principles of materials science as viewed by other disciplines. The HCF facility provides the opportunity for students to acquire skills in high cycle fatigue characterization in gaseous environments at high temperature.

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