High Temperature Static Strain Sensor Development Program

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United Technologies Research Center
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The purpose of this program is to develop resistance strain gages useful for static strain measurements on nickel or cobalt superalloy parts inside a gas turbine engine on a test stand. Measurements of this type are of great importance in meeting the goals of the Host Program because, without reliable knowledge of the stresses and strains which exist in specific components, it will be difficult to fully appreciate where improvements in design and materials can be implemented. The first year of effort has consisted of a strain gage alloy development program which is to be followed by an optional second year of work to investigate complete strain gage systems which will use the best of the alloys developed together with other system improvements.

The specific goal for the complete system is to make measurements to 2,000$\mu\varepsilon$ with error of only $\pm$ 10% over a 50 hour period. In addition to simple survival and stability, attaining a low thermal coefficient to resistivity, of order 100 ppm/K or less, is also a major goal. This need results from the presently unavoidable uncertainty in measurements of the exact temperatures in the turbine. The size and thickness requirements to avoid aerodynamic effects suggests the use of the sputtering technique as the best system fabrication approach. The first task of the program was to select candidate alloys or alloy systems using a search of the literature and the available metallurgical theory. Alloy candidates were evaluated and compared using a grading system consisting of the product of the following factors with their total weight potential given in parentheses: Repeatability (20), Oxidation (18), Resistivity (16), Thermal coefficient of resistivity (14), Elastic range (12), Differential thermal expansion (10) and Miscellaneous judgments (10). After discussion and review with NASA, the following alloys, indicated in weight percent, were deemed the best candidates: 45Pt-45Pd-10Mo, 60Pd-30Ag-10Mo, FeCrAl type, 84.4Ni-14.2Cr-1.45Si, Pt-10W and Pd-30 Cr.

In addition, fabrication and test plans were also developed and given NASA approval. The initial intention was to fabricate alloy samples by sputtering on thin alumina substrate plates. Because of the possibilities of delays and that it would probably be difficult to screen many alloys within the time constraints of the program, the alternative approach of drop casting directly into wire form was adopted. In this process, small buttons of the alloy were repeatedly melted on a cold copper or tungsten hearth using tungsten electrodes and then cast inside tubes of SiO_2 or Al_2O_3 by suddenly changing the pressure of the argon cover gas. Partly because of the simplicity of this approach, we were able to make evaluations on a total of 37 different samples of 29 different compositions which can be compared with a maximum of 12 alloy samples required by the work statement.

A specially constructed thermal cycling apparatus was developed to make resistivity measurements by the use of a split metal tube heater which could be cycled or held at a constant temperature under program control. The test sample was positioned axially in the center of this tube with Platinum leads for voltage measurements and five thermocouple wires attached in the constant temperature section by spot welding. Part of the way through the test program, a H.P. 9826A computer and a voltmeter capable of measurement down 100 nanovolts were added to the apparatus.

The first part of the experimental program consisted of homogenizing the cast samples via heat treatments followed by metallographic and/or SEM investigations of the microstructures produced to verify that they were essentially phase pure. Measurements of electrical resistivity, the continuous measurement of the changes in resistivity for samples cycled from R.T. to 1250K at 10,50 and 250K/min. and drift of resistance with time at 1250K were then made for each alloy. This series of tests was iterated for at least a total of six different alloy compositions of each alloy type unless the data obtained suggested that experiments with that type be discontinued. Significant problems of immiscibility in Pd-Ag-Mo resulted in that system being dropped. Work on Nicrosil (84.4Ni-14.2Cr-1.4Si) was also discontinued because of a high thermal rate sensitivity and apparent metallurgical instability at about 900K. The alloy compositions judged to be the best using the evaluation process described above were: 48Pt-40Pd-12Mo, 77Pt-6.5W-6.5Re, 77.5Fe-11.9Al-10.6Cr and 83Pd-13Cr-4Co (in weight percent).

The second part of the test plan consisted of evaluations of the oxidation resistances, chemical compositions, thermal expansions, melting points, stress-strain and creep behavior of the best alloys of each type discovered in part one. The oxidation testing consisted of periodic measurements of weight change during a 50 hour exposure to air at 1250K. As was predicted, the Pd-13Cr-4Co and FeCrAl modification #3 gained in weight while the Pt-W and Pt-Pd-Mo alloys lost weight. The total weight grain of Mod #3, approximately 0.3 mg/cm^2, was slightly greater than that for Kanthal A-1 which is an alloy known for its good resistance to oxidation. All the other FeCrAl alloys lost weight because the coatings were nonprotective and spalled off.

The final part of the test program consisted of an attempt to demonstrate that sputtered films, after being fully stabilized and annealed, had essentially the same electrical properties as the cast material of identical composition. Sputtered samples, approx. 1.3 microns thick, were prepared of FeCrAl Mod #3 and Kanthal A-1 for comparison. Attempts to test the Kanthal A-1 sample resulted in erratic results and finally failure of the gage to conduct. The problem was traced to oxidation caused by small amounts of oxygen in the argon purge gas. The oxide films were not completely continuous. Those results suggested that much thicker sputtered films are required.

In summary, equipment and techniques were developed suitable for iterative studies of a variety of compositions. Many compositions were examined and some significantly improved alloys were identified. Additional iterative alloy development work is desirable, especially with regard to the electrical and environmental stability of (coated) sensor gages.

OBJECTIVE:
DEVELOP IMPROVED STATIC STRAIN GAGE ALLOYS

- Useful to 1250K
- 50 hrs. life
- 2,000 $\mu\epsilon$, ± 10%
- Jet engine environment

TEST PLAN

Part I - Measure ρ , α & drift at 1250K iterate

Part II - Determine additional properties of selected alloys

Part III - Demonstrate transfer of properties to sputtered thin films

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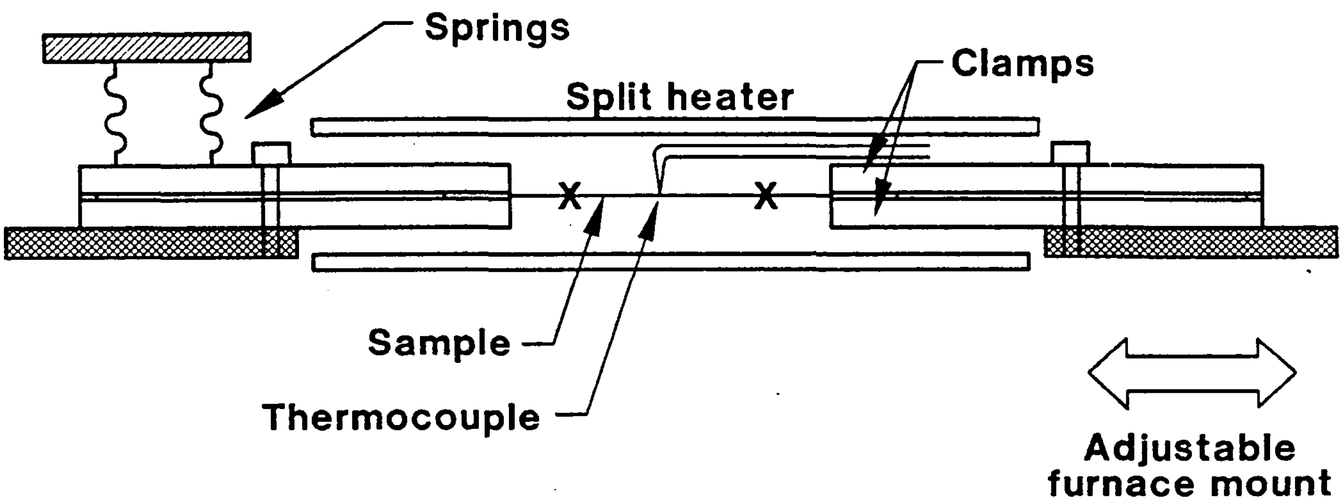
HIGH-SPEED THERMAL CYCLE/ RESISTIVITY MEASUREMENT APPARATUS



RANKING METHODOLOGY

Factors	Scale
Repeatability, R	1 - 20
Oxidation, O	1 - 18
ρ	1 - 16
α	1 - 14
ϵ_{el}	1 - 12
ΔCTE	1 - 10
Judgment, J	1 - 10

Σ upper scale factors = 100

$$\text{Ranking} = (R)\cdot(O)\cdot(\rho)\cdot(\alpha)\cdot(\epsilon_{el})\cdot(\Delta\,\text{CTE})\cdot(J)$$

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RANKING OF ALLOY COMPOSITIONS

Alloy type	Rank 3/10/82	Rank 8/25/82
FeCrAl, A-1 Fe-22Cr-5.5Al-0.5Co	9.2	
FeCrAl, Mod. #3 Fe-11.9Al-10.6Cr		83.8 *
Nicrosil Ni-14.2Cr-1.4Si	110.9	16.1
45Pt-45Pd-10Mo	148.3	

* = recommended

RANKING OF ALLOY COMPOSITIONS (Cont.)

Alloy type	Rank 3/10/82	Rank 8/25/82
48Pt-40Pd-12Mo Mod. #4		42.6
Pd-20Cr	94.1	
Pd-13Cr-4Co		44.2
Pt-10W	57.6	
Pt-6.5W-6.5Re		145.2*
Pd-Ag-Mo	Immissibility - Alloy dropped	

* = recommended

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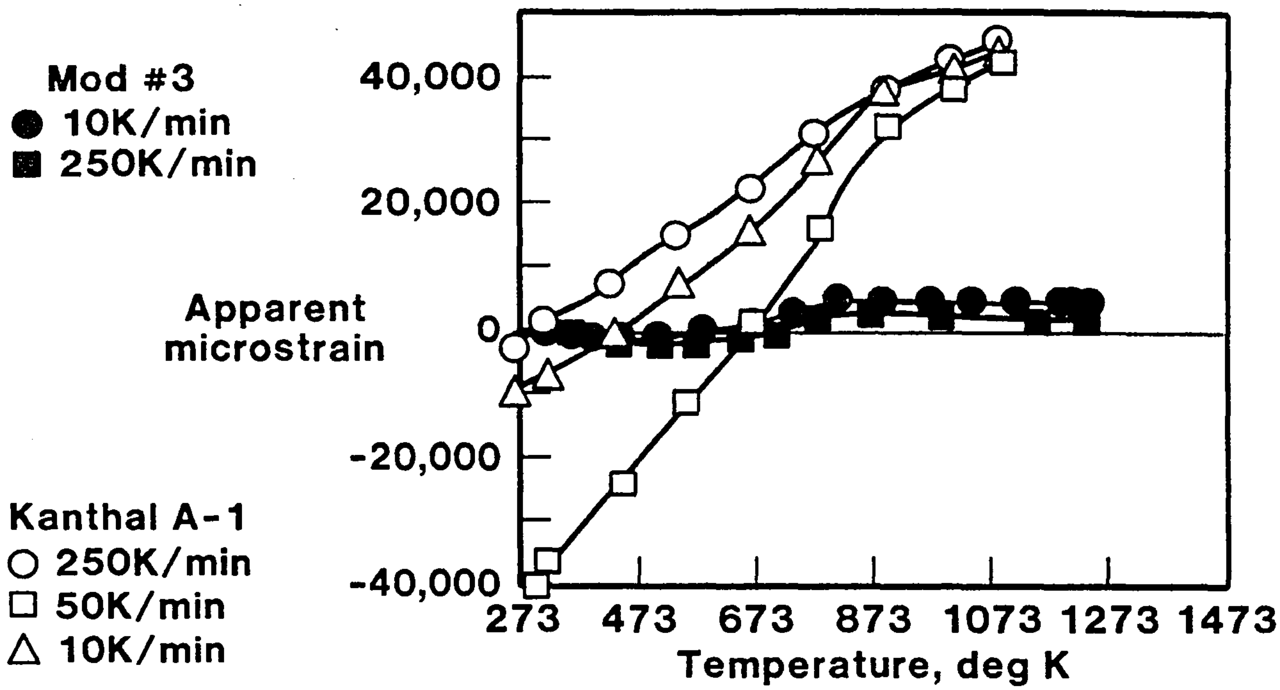
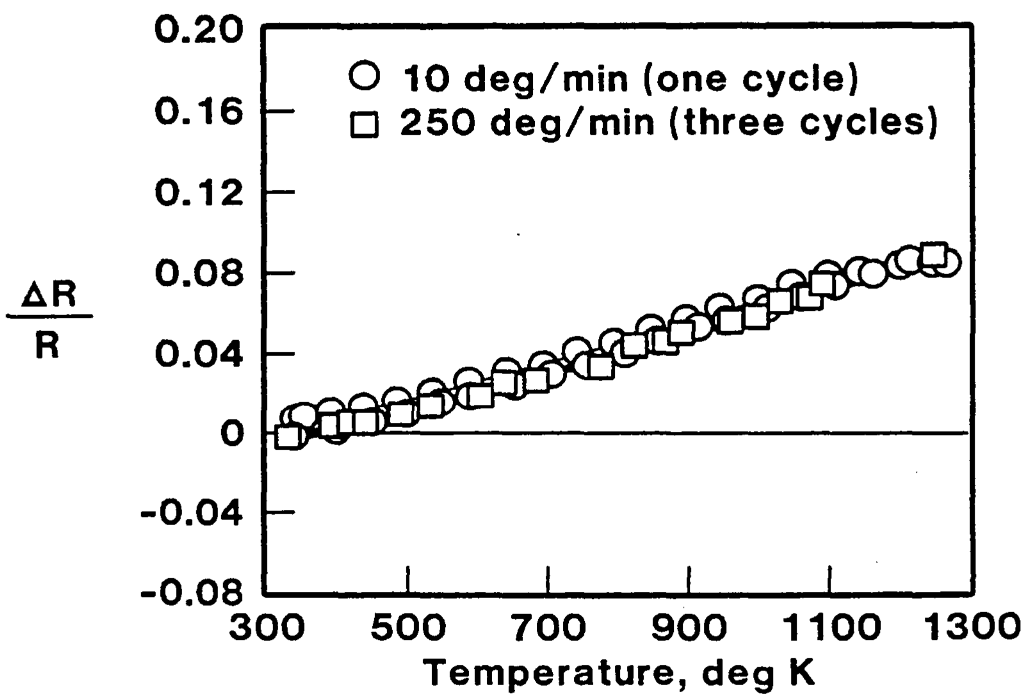
KANTHAL A-1 AND FeCrAl MOD #3 AFTER 2 HRS. AT 1153°K



ELECTRICAL RESISTANCE FOR Pt-6.5W - 6.5 Re vs TEMPERATURE



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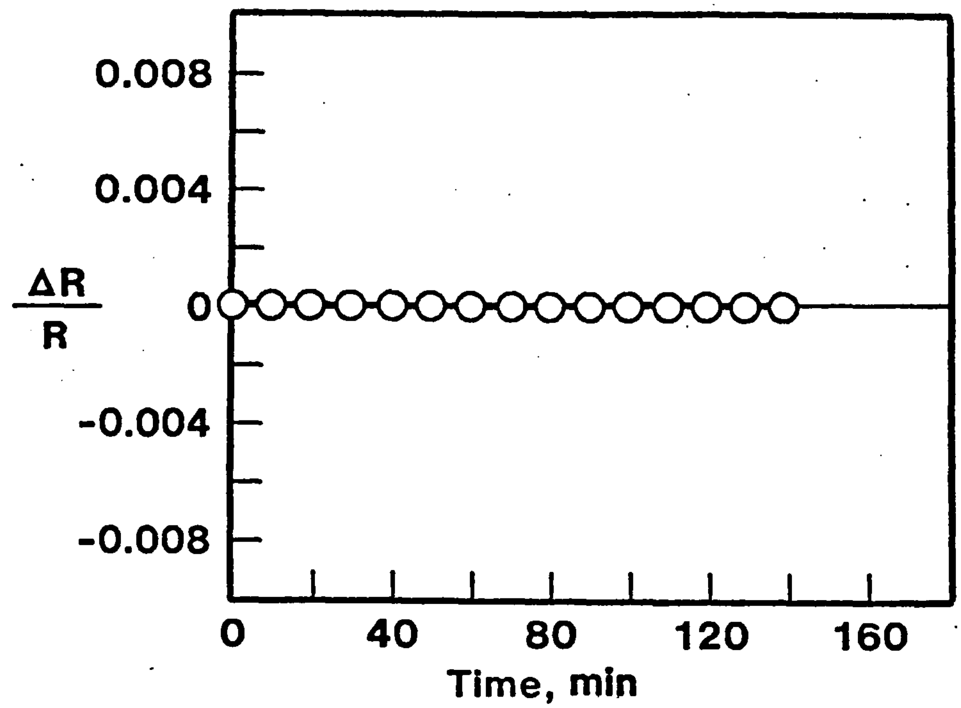
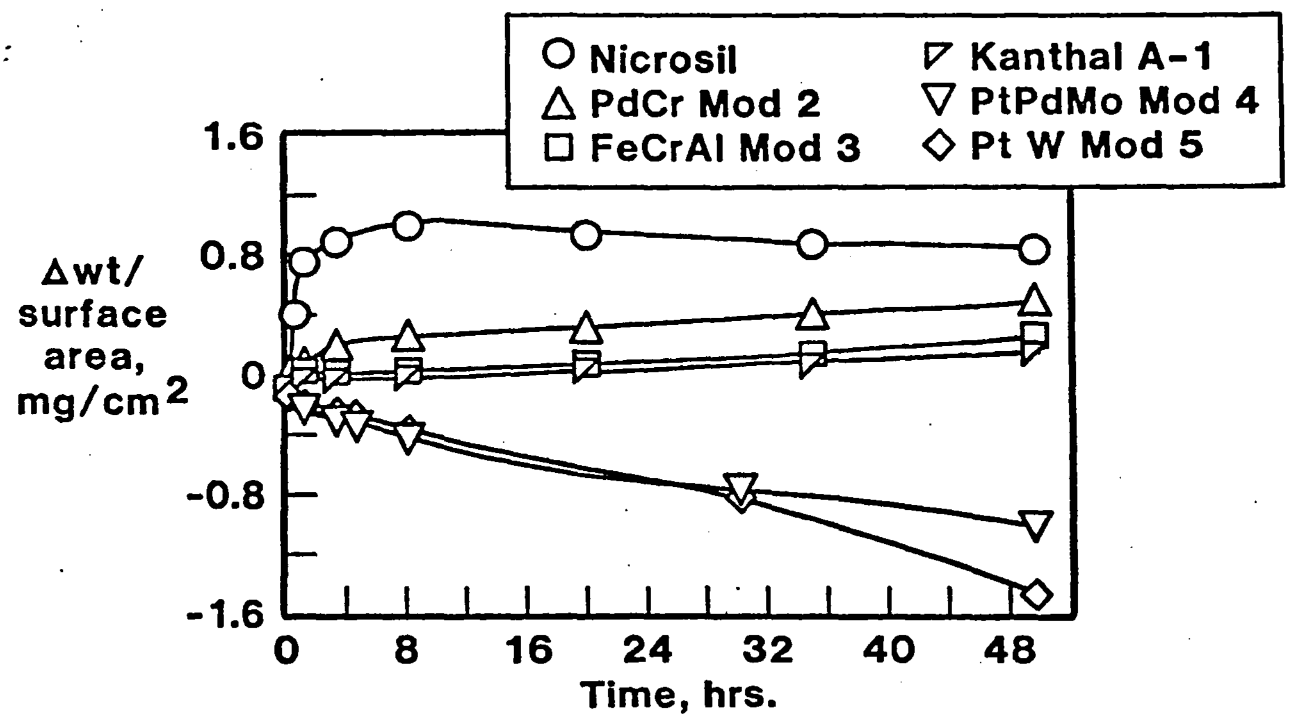
RESISTANCE DRIFT OF FeCrAl MOD #3 AT 1250°K



WEIGHT CHANGE OF STRAIN GAGE ALLOYS EXPOSED TO AIR AT 1250°K



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MAJOR RESULTS

- Testing facilities developed
- Simple fabrication technique established
- Numerous compositions examined
- Pt-W-Re and FeCrAl alloy identified
- Oxidation & strain range limitations observed
- Further optimization advisable

STATUS

- Improved compositions discovered
- Optimization desirable

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