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REVIEW OF THE AGARD S & M PANEL EVALUATION PROGRAM OF THE NASA-LEWIS "SRP" APPROACH TO HIGH-TEMPERATURE LCF LIFE PREDICTION

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REVIEW OF THE AGARD S&M PANEL EVALUATION PROGRAM OF THE NASA-LEWIS "SRP" APPROACH TO HIGH-TEMPERATURE LCF LIFE PREDICTION.

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SUMMARY

Twenty laboratories in six countries participated in this program, each testing its own materials of interest under its own laboratory conditions. In this way the results obtained provided validation of the Strainrange Partitioning (SRP) method for a wide range of materials and insured maximum usefulness to each of the participating laboratories. The first, very necessary step in the evaluation of any life prediction approach - assessing the ability of the method to predict life of simple laboratory specimens subjected to complex loading, was thereby taken. The culmination of this program was the Specialists Meeting that was held in Aalborg, Denmark in April of 1978. At that meeting the various investigators shared their findings, thus providing the basis for an in-depth evaluation of the SRP method. While the results were variable from laboratory to laboratory, most investigators agreed that the SRP method was a significant step toward life prediction in the presence of high temperature and cyclic stresses.

INTRODUCTION

Since advanced turbine engine materials for military applications are being used to a high fraction of their ultimate capabilities, there is a great need for more meaningful high temperature mechanical property tests on these materials as well as for improved analytical techniques for predicting their service life. One particularly vexing problem has been the difficulty in describing and predicting the behavior of materials subected to the high temperatures and the loading conditions, such as creep-fatigue interactions, encountered in engine component service. The panel, has made an attempt to address this problem by supporting a cooperative program aimed at the evaluation of the Strainrange Partitioning (SRP) approach for the analysis and prediction of low-cycle high temperature fatigue life. This approach involves an entirely different way of dealing with creep-fatigue interaction than considered heretofore and is a product of the high temperature fatigue research conducted at the NASA Lewis Research Center.

WHAT IS SRP?

Since the early 1950's, a variety of materials characterization and life prediction techniques have been developed to fulfill the immediate needs of designers and builders of high-performance, energy-conversion equipment that must operate reliably for long periods of time at high temperatures. Although most of the approaches offered some unique advantage, they all had deficiencies of one sort or another. Also, since the early 1950's a large quantity of high temperature, low-cycle fatigue data has been generated on a host of alloys. In many instances these data were determined to answer a single specific question relative to a particular design requirement, and little regard was given to the generation of data that would have general applicability to future problems. As a consequence, the designer is faced with a choice of life prediction techniques and a vast quantity of diverse, sometimes contradictory, and often inappropriate low-cycle fatigue test data.

It was out of this environment that the SRP approach was formulated in 1971 (ref. 1). In the intervening years we have developed considerable insight into its capabilities and recognize the technological impact the approach offers in the design of components that must resist failure due to the interaction of high temperature creep and fatigue. The primary advantage of SRP rests on its high degree of generality. Relatively few test data are necessary to characterize a material in terms of SRP, and the results are applicable to complex strain cycles. Not only is the approach a general and fundamental one, but it also appears to offer better accuracy than other available methods in predicting life than has been possible heretofore (ref. 2).

REVIEW OF SRP CONCEPTS

The Lewis Research Center has long been involved in the development of theories and approaches for dealing with low-cycle fatigue behavior of materials. A most important transition from a stress approach to a strain approach occurred with the formulation of the Manson-Coffin law (ref. 3). We then went to the total strain approach with the inclusion of the elastic portion of the total strainrange (ref. 4). The Manson-Hirschberg method of universal slopes was then developed (ref. 5), which made it possible to estimate total strainrange versus life behavior from conventional short-time tensile properties. It was, of course, recognized that these approaches were all limited to temperatures below the creep limit. Our first attempts to account for creep effects were the 10 percent rule (ref. 6) and the creep-modified 10 percent rule (ref. 7). These techniques represented most of the available high temperature test data well, but they were not sufficiently conservative for cases involving long hold times or where large creep strains could be accumulated. An attempt to remedy this was made with the life fraction approach (ref. 8). Unfortunately, that method involves extensive analytical procedures and was unable to explain some of the experimental observations regarding the damaging effects of compressive stress. The next step was the formulation of the SRP method which holds promise for overcoming deficiencies in previous methods.

The basic premise for SRP is that in any hysteresis loop there are combinations of just two <u>directions</u> of straining and two <u>types</u> of inelastic strain. The two directions are, of course, tension (associated with a positive inelastic strain rate) and compression (associated with a negative inelastic strain rate); the two types of inelastic strain are time dependent (creep) and time independent (plastic). By combining the two directions with the two types of strain, we arrive at four possible kinds of strainranges that may be used as basic building blocks for <u>any</u> conceivable hysteresis loop. These define the manner in which a tensile component of strain is balanced by a compressive component to close a hysteresis loop. What was next proposed, was that the Manson-Coffin relationship (which represents the inelastic strainrange versus life behavior for materials below the creep limit) be expanded to four relationships for dealing with materials above the creep limit.

Once these relationships have been generated for a material, there remains the question of how to to apply them to a more complex loading problem in order to predict life. This is accomplished in two parts. First, the hysteresis loop for the cycle being analyzed must be partitioned into its inelastic components. Second, a damage rule, which we have developed and termed the interaction damage rule, is applied in order to predict the life associated with the combination of applied strainranges.

It is this total process of generating the individual failure life relationships, partitioning a hysteresis loop into its component strainranges, and combining the effects of these components to determine life, that we have called the SRP method. References 9-21 contain descriptions of all the various aspects of SRP as well as several examples of the ability of the method to correlate and predict the fatigue life of specimens subjected to complex loading conditions.

THE COOPERATIVE EVALUATION PROGRAM FOR SRP

Background

The AGARD Structures and Materials Panel has had a long and active interest in researching subjects that are of a critical nature and of common interest to the NATO community. In keeping with this tradition, the Panel, in the Spring of 1971 deemed it highly advisable to initiate specific activities in the area of low cycle high temperature fatigue (LCHTF).

At the Fall 1972 S&M Panel Meeting, Mr. Drapier, who was charged by AGARD with the coordination of the various activities on this subject, submitted a document entitled "Ad Hoc Group on Low Cycle High Temperature Fatigue - Status Report" (ref. 22), which reviewed the LCHTF work being carried out by the laboratories in the various NATO nations interested in this problem. In the fall of 1973, Mr. Drapier presented to the S&M Panel his in-depth report entitled "Survey of Activities in the Field of Low Cycle High Temperature Fatigue" (ref. 23).

Through the continuing efforts of Mr. Drapier, supported by this Panel, AGARD has published a volume containing the papers presented at the Specialists Meeting on Low Cycle High Temperature Fatigue (ref. 24) held in Washington D.C. in April of 1974. At this meeting, experts were invited to provide replies to a number of questions raised by the organizers; each subject was introduced by a paper, the purpose of which was to survey the problem areas associated with that subject and to orient and focus the subsequent discussion.

One of the conclusions of the above noted Specialists Meeting was the recognition of the need for more reliable life prediction methods that are applicable to LCHTF gas turbine components. It was in the spring of 1975 that this author presented an invited pilot paper to the AGARD Working Group on High Temperature Materials, suggesting a cooperative program aimed at evaluating the ability of the SRP method to predict life in the creep-fatigue range. This program was approved by the S&M Panel and Messrs Hirschberg and Drapier were designated program coordinators. The laboratories surveyed (ref. 23) were then contacted by the coordinators and invited to participate in the program.

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Program Objectives

Twenty laboratories in six countries participated in this program, each testing its own materials of interest under its own laboratory conditions so that that the results obtained would provide validation for a wide range of materials and would insure maximum usefulness to each of the participating laboratories. In using a common set of definitions, data sheets, and format for data presentation, it was also possible to collect and tabulate the various sets of data and present them as a single body of high temperature creep-fatigue data. The objective here, was to produce a reference body of data easily usable by any other investigator. What we have taken here, was the first, very necessary step in the evaluation of a life prediction approach - the evaluation of the ability of this method to predict the life of specimens subjected to complex loading from specimen data obtained from simple tests. One could not hope to obtain reliable life predictions for engine components if it were not possible to reliably predict the lives of well controlled laboratory specimens. The culmination of this program was a Specialists Meeting held in April of 1978, that brought together the investigators with the objective of sharing their laboratory testing experiences to permit an in-depth evaluation of the SRP method, and provide maximum exposure to the findings and recommendations of a distinguished body of specialists.

Program Organization

The program was organized and conducted by the two coordinators appointed by AGARD. Mr. Drapier acted as the focal point for coordinating the activities among the European participants and this author had the equivalent responsibilites for the U.S. participants. In the initial phase of this activity, Mr. Drapier had the responsibility of surveying numerous laboratories in the NATO community to determine their interest in participating. Mr. Drapier was in an excellent position to make this survey since he had previously made another survey in this area (ref. 23). Once the interested laboratories had been determined, a NASA report (ref. 25) was sent to each describing in detail what SRP was, how SRP tests could be run, and suggesting numerous aspects of SRP that needed broader verification. This report was translated into both French and German and made available to those selected laboratories as well. Sufficient time was given for the review of this report and those laboratories which initially expressed interest were again surveyed to finally establish whether or not they wished to participate in the program. Once this was determined, the coordinators then constructed a timetable for the program, that included such items as interim program review meetings (described in Mini-Symposia section), dates for completion of the testing portion of the program as well as for the written final report, and the final Specialists Meeting. The coordinators were also responsible for arranging the Specialists Meeting and assembling the final AGARD Report containing the papers and discussions held at this meeting.

Program Participants

Table I lists the principal participants in this program along with their organizations. There were of course many other persons involved in the individual testing programs as well as those that contributed to the success of the Specialists Meeting. These names and organizations are far too numerous to list here. Most of these persons can, however, be identified in the AGARD publication of the proceedings of the meeting (ref. 26).

Program Data Generation and Collection

In order to be able to easily construct a set of tables describing all the data generated in the evaluation program, it was necessary to first agree upon common definitions and terms, as well as data sheets that all the participants could use. The data sheets were used for reporting all the fatigue data, as well as background information defining the materials used in the investigations. This information included chemical composition, material processing and heat treatment, and the conventional mechanical properties for each of the alloys tested. These data sheets were used to ensure that pertinent information was reported in a consistent manner. One of the sample data sheets is shown in Table II. Copies of all the data sheets were sent to the NASA Lewis Research Center where Mr. J.F. Saltsman transcribed the information to a computerized format for ease of storage, analysis, and retrieval.

Mini-Symposia

One of the prime reasons for the success of this activity was the interaction afforded the investigators from the mini-symposia. They provided the opportunity for critical in-depth interchanges of ideas, concerns, testing techniques, as well as the evaluation of test results that were a benefit to all the participants.

In order to assure maximum participation in these symposia, separate meetings were held in the U.S. and in Europe. During the course of the evaluation program, Mr. Drapier arranged three meetings for the European participating laboratories. They were held at the National Physical Laboratory in England, the Center for Metallurgical Research in Belgium, and the National Gas Turbine Establishment in England. This author arranged three similar meetings for the U.S. participating laboratories. Two such meetings were held at the NASA Lewis Research Center and one at the Air Force Materials Laboratory. This author was the only one who attended all six symposia and was thereby able to keep the laboratories on both sides of the Atlantic informed and up to date regarding all aspects of the SRP evaluation program. In addition to reports presented orally by this author at each symposia, meeting minutes were distributed to all the participating laboratories.

RESULTS OF THE SRP EVALUATION PROGRAM

The culmination of the SRP cooperative evaluation program was an AGARD sponsored Specialists Meeting where papers were presented, and where extensive discussions were held. These papers, including their individual evaluations and recommendations regarding the SRP method, as well as all the tabulated test data are given in reference 26. A brief review of these follows:

Specialists Meeting

The Specialists Meeting was held in Aalborg, Denmark on the 11th and 12th of April, 1978. Seventeen presentations were made in three separate sessions with a fourth session devoted entirely to discussion. Preprints for all of the presentations were available at the meeting and had been distributed to all the speakers prior to the meeting. Recorders were assigned to each of the sessions for the purpose of documenting the sense of the discussions that followed each session. The condensation of these discussions also appears in reference 26.

Data Tabulation

All of the data collected from the participating laboratories were tabulated in a common format and appear in the appendix of reference 26. In this form, it represents an extremely valuable body of creep-fatigue data covering a variety of engineering alloys. As much of the raw data as possible were included in the tabulations so that future analyses and interpretations can be made with a minimum of effort and a maximum of reliability. An example of the creep-fatigue test data for one alloy is shown in Table III.

Evaluation of the SRP Method

The general consensus of the investigators involved in this program was positive and in agreement that the SRP method was a significant step foward in high temperature low-cycle fatigue life prediction. There did emerge from this program several concerns and recommendations regarding SRP. These dealt primarily with the problems associated with the application of SRP to cases involving small inelastic strains (and therefore long lives). The difficulties associated with partitioning these narrow hysteresis loops and the present inability of SRP to handle mean stress effects were also noted. The specifics regarding these concerns and recommendations can be found in the individual papers of reference 26.

CONCLUSIONS

In as much as this cooperative evaluation program was the result of a request of the AGARD S&M Panel Sub-Commitee on High Temperature Materials, it would be desirable to review their conclusions regarding this program. The following was extracted from the Summary Record of the 46th Panel Meeting:

"Informal discussions were held with the members of the Sub-Committee with the following conclusions:

The Strainrange Partitioning Cooperative Program was an outstanding success because

a) it provided an additional 19 laboratories in 6 NATO nations with a new method for physical testing

b) it provided a broad base of experience in using the new approaches and the methods for handling the data

c) while the results were variable from laboratory to laboratory, most investigators agreed that the strainrange partitioning method was a significant step toward life prediction in the presence of high temperature and cyclic stresses. ..... "

The above is in effect an integration of all the conclusions of the individual participants in this program. Each of the investigators have included their own conclusions in their written papers and these are available in reference 26.

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TABLE I

CONTRIBUTORS TO THE SRP EVALUATION PROGRAM

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TABLE II

SAMPLE DATA SHEET

STRAINRANGE PARTITIONING TEST SUMMARY RECORD		1
GENERAL INFORMATION		
1 Name of laboratory	2 Responsible engineer	3 Date of test
4 Material designation	5 Material heat number	6 Specimen number
7 Test type (See definitions)	8 Sketch of strain-time waveform	9 Temperature of test, °C
RATE DATA (Half Life Values)		
10 Cyclic frequency, Hz	11 Tensile strain rate, %/sec	12 Compressive strain rate, %/sec
13 Tensile hold time, sec	14 Compressive hold time, sec	15
16	17	18
STRESSES (Half Life Values) in units of MPa		
19 σ_t	20 σ_c	21 $\Delta\sigma$
22 $\Delta\sigma_t$	23 $\Delta\sigma_c$	
24 Cyclic strain hardening ______ % change in stress range from 1st to half-life cycle Cyclic strain softening ______ % change in stress range from 1st to half-life cycle		
STRAINS (Half Life Values) in units of %		
25 $\Delta\varepsilon_t$	26 $\Delta\varepsilon_{in}$	27 $\Delta\varepsilon_{el}$
28 $\Delta\varepsilon_{pp}$	29 $\Delta\varepsilon_{pc}$	30 $\Delta\varepsilon_{cp}$
31 $\Delta\varepsilon_{cc}$	32	33
FAILURE DATA		
34 N_0, cycles to first indication of cracking (note method of detection)		
35 N_t, cycles when ratio of max tensile to max comp. stress decreases 10% from half-life or stabilized value		
36 N_5, cycles when stress range decreases by 5% from half-life or stabilized value		
37 N_f, cycles for complete fracture		
38 t_f, test time for complete fracture, hours		
39		
40		
41		

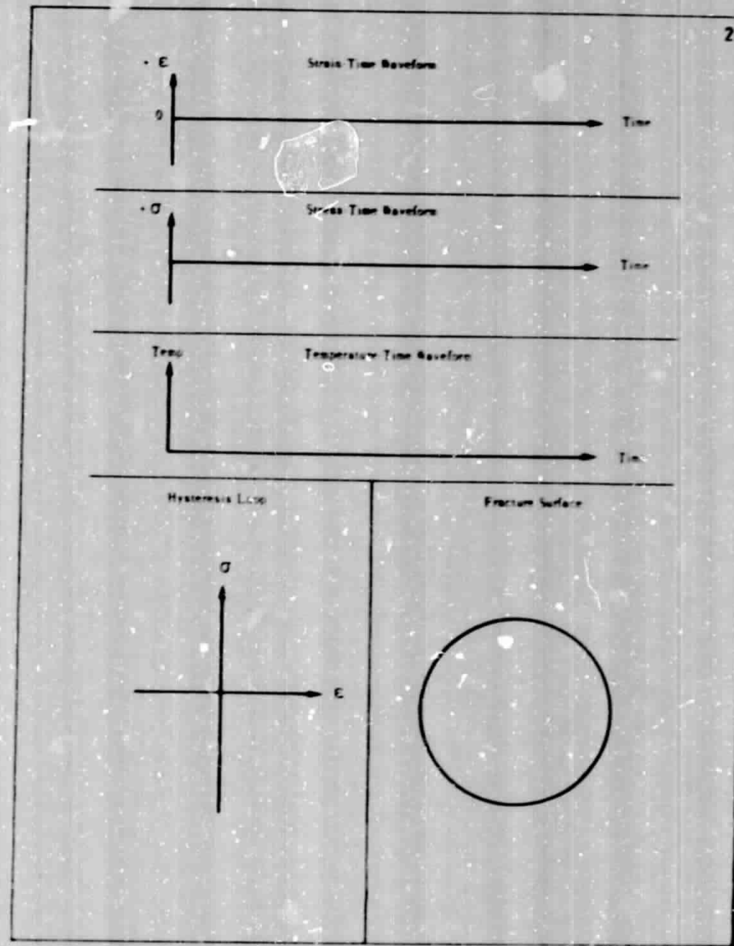

TABLE III

LABORATORY: NPL
MATERIAL: IN738LC

CREEP-FATIGUE DATA

RATE DATA & STRESSES

SPEC NO	TEST TYPE	TEMP-C TEN/COMP	RATE DATA(HALF-LIFE VALUES) FREQ HZ	STRAIN-RATE-%/SEC TEN	STRAIN-RATE-%/SEC COMP	HOLD TIME-SEC TEN	HOLD TIME-SEC COMP	STRESSES(HALF-LIFE VALUES) MPA TEN MAX	COMP MAX	RANGE MAX	RELAXATION TEN	RELAXATION COMP	CYCLIC STRAIN HARDENING %
DCH28	HRSC	850/850	8.0E-01	1.3E 00	1.3E 00	0	0	343.0	542.0	885.0	0.0	0.0	-5.00
DCH42	HRSC	850/850	2.5E-01	1.0E 00	1.0E 00	0	0	892.0	916.0	1808.0	0.0	0.0	-4.00
DCH79	HRSC	850/850	5.0E-01	1.0E 00	1.0E 00	0	0	427.0	648.0	1075.0	0.0	0.0	-33.00
DCH85	HRSC	850/850	3.8E-01	1.0E 00	1.0E 00	0	0	751.0	826.0	1577.0	0.0	0.0	--
DCH41	BCCR	850/850	7.8E-03	7.0E-01	7.0E-01	50.0	75.0	350.0	350.0	700.0	0.0	0.0	--
DCH43	BCCR	850/850	6.5E-03	1.0E 00	1.0E 00	75.0	100.0	400.0	400.0	800.0	0.0	0.0	--
DCH73	BCCR	850/850	1.0E-03	1.0E 00	1.0E 00	250.0	700.0	550.0	550.0	1100.0	0.0	0.0	--
DCH94	BCCR	850/850	9.6E-03	1.0E 00	1.0E 00	38.0	63.0	450.0	450.0	900.0	0.0	0.0	--
DCH39	CCCR	850/850	3.6E-03	1.0E 00	1.0E 00	0	275.0	930.0	500.0	1430.0	0.0	0.0	--
DCH40	CCCR	850/850	8.3E-02	1.0E 00	1.0E 00	0	10.0	690.0	400.0	1090.0	0.0	0.0	-8.00
DCH45	CCCR	850/850	3.7E-02	7.0E-01	7.0E-01	0	25.0	455.0	300.0	755.0	0.0	0.0	--
DCH67	CCCR	850/850	6.8E-02	1.0E 00	1.0E 00	0	12.0	731.0	400.0	1131.0	0.0	0.0	-7.50
DCH46	TCCR	850/850	7.5E-02	8.0E-01	8.0E-01	12.0	0	300.0	710.0	1010.0	0.0	0.0	-5.00
DCH66	TCCR	850/850	2.1E-02	9.0E-01	9.0E-01	45.0	0	350.0	846.0	1196.0	0.0	0.0	-3.00
DCH68	TCCR	850/850	9.8E-03	8.0E-01	8.0E-01	100.0	0	190.0	640.0	830.0	0.0	0.0	-3.00
DCH93	TCCR	850/850	1.7E-03	1.0E 00	1.0E 00	600.0	0	450.0	958.0	1408.0	0.0	0.0	-3.50

STRAINS & FAILURE DATA

SPEC NO	STRAINRANGES(HALF-LIFE VALUES) % TOTAL	EL	IN	PP	PC	CP	CC	FAILURE DATA-CYCLES NO	NI	N5	NF	TF-HRS
DCH28	0.700	0.668	0.032	0.032	0.000	0.000	0.000	--	--	--	6178	1.92
DCH42	2.000	1.160	0.845	0.845	0.000	0.000	0.000	--	--	--	19	0.01
DCH79	1.000	0.920	0.080	0.080	0.000	0.000	0.000	200	--	45	475	0.13
DCH85	1.300	1.040	0.257	0.257	0.000	0.000	0.000	--	--	--	160	0.12
DCH41	0.700	0.530	0.168	0.032	0.000	0.000	0.136	1500	--	--	221[illegible]	22.90
DCH43	1.000	0.590	0.410	0.120	0.000	0.000	0.290	90	--	--	[illegible]	14.50
DCH73	2.000	0.655	1.345	0.200	0.000	0.000	1.145	--	--	--	3	0.68
DCH94	1.300	0.726	0.574	0.231	0.000	0.000	0.343	40	--	--	74	7.70
DCH39	2.000	0.770	1.230	0.430	0.600	0.000	0.000	--	--	--	15	1.00
DCH40	1.000	0.730	0.270	0.170	0.100	0.000	0.000	115	--	105	228	1.56
DCH45	0.700	0.640	0.057	0.036	0.021	0.000	0.000	850	--	750	1259	16.00
DCH67	1.300	0.880	0.420	0.250	0.170	0.000	0.000	94	--	82	210	1.20
DCH46	1.000	0.800	0.197	0.113	0.000	0.084	0.000	700	--	550	1036	4.30
DCH66	1.300	0.890	0.410	0.200	0.000	0.210	0.000	65	--	70	92	2.80
DCH68	0.700	0.566	0.134	0.087	0.000	0.047	0.000	2000	--	1950	2099	48.20
DCH93	2.000	0.840	1.160	0.285	0.000	0.875	0.000	15	--	18	25	4.60

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16. Abstract

Twenty laboratories in six countries participated in this program, each testing its own materials of interest under its own laboratory conditions. In this way the results obtained provided validation of the Strainrange Partitioning (SRP) method for a wide range of materials and insured maximum usefulness to each of the participating laboratories. The first, very necessary step in the evaluation of any life prediction approach - assessing the ability of the method to predict life of simple laboratory specimens subjected to complex loading, was thereby taken. The culmination of this program was the Specialists Meeting that was held in Aalborg, Denmark in April of 1978. At that meeting the various investigators shared their findings, thus providing the basis for an in-depth evaluation of the SRP method. While the results were variable from laboratory to laboratory, most investigators agreed that the SRP method was a significant step toward life prediction in the presence of high temperature and cyclic stresses.

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