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A STUDY ON PREVENTION OF CREEP AND FATIGUE FRACTURE OF STEELS FOR TURBINE APPLICATION

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INTRODUCTION

Based on today's electrical energy supply system conditions, it is necessary that components of modern turbines up to largest unit capacities are not only able to operate under steady state loading - lasting more than 20 years - but they must in addition be able to take more than 10^4 start ups and power transients without fatigue cracks. Figure 1 displays loading cycles, which occur i.e. in a high pressure turbine casing during a semi hot start up after a weekend shut down, at 50 per cent load change and at a hot start up after 9 hours night shut down.

Results of low cycle fatigue test are suitable for calculating allowable temperature rates in non-steady processes. The cycles of these tests should be accommodated as much as possible to those of actual non-steady service conditions. Published investigations however often differ fundamentally in test parameters. Essential are the differences in loading conditions (i.e. bending or push-pull), in determination of crack initiation and in the type of cycle. In the majority of cases tests were run with hold times in tension only [1-3], although component surfaces contacted by the working medium are compressively strained during temperature elevation for a period longer than the tensile hold time.

OWN INVESTIGATIONS

It was the aim of these investigations to obtain the relation of numbers of cycles to crack initiation by an isothermal push-pull test, run with types of cycles similar to those in service [4] and [5] for some German standard heat resistant turbine materials. Under thermal loading the strain in a component is always superimposed by a temperature change, that is strain and temperature change at the same time. Therefore, the question arose whether differences exist between low cycle fatigue tests at constant and under cyclic temperatures. To answer this, torsional strain cycling tests were run under simultaneously cycling temperatures, since under torsional loading it is easy to guarantee free thermal expansion of the specimens in the longitudinal direction. All tests were performed in servo-hydraulic closed loop controlled machines.

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Test Parameters

- i) strain rates 0.02 to 6%/min
- ii) different hold times, max. 180 minutes in tension and/or compression loading (≤ 180 minutes)
- iii) isothermal tests at 20 to 600°C, tests with simultaneous strain and temperature cycling between 200 and 600°C
- iv) smooth and notched specimens
- v) different surface conditions

In all tests the number of cycles to crack initiation was defined by a distinct drop of stress occurring on the tension side of the cycle in the continuously written stress-time record.

Materials

Six different heat resistant ferritic steels were tested. Table 1 gives the chemical composition and Table 2 the heat treatment and mechanical properties.

TEST RESULTS

Comparison of Materials

Figure 2 gives a comparison of 530°C test results with twenty minutes hold time each in tension and compression (± 20 minutes hold time) for five different alloyed forged and cast steels, for lives up to 10^3 strain cycles. The low cycle fatigue behaviour of these materials is nearly equivalent within the range of number of cycles tested.

Influence of Hold Time

Figure 3 shows the results of tests on 1%CrMoV type cast steel GS-17 CrMoV 5 11, German standard DIN 17 245, at 530°C with hold times up to ± 90 minutes. Corresponding to our expectation the specimens loaded only with hold times in compression behave more advantageously than those which were tested with hold times in tension only or in tension and compression. In addition to this the results show that in the range above 10^3 cycles the influence of hold times on number of cycles to crack initiation is still pronounced.

Influence of a Weldment

With consideration of rectification welding, which is always necessary on large turbine casings during manufacturing, specimens from a manual metal arc welding on the GS-17 CrMoV 5 11 were tested in low cycle fatigue at 530°C with and without hold times (± 20 minutes). The specimens from both weld and base material were cut parallel to the longitudinal direction of the weldment so that the position of the heat affected zone (HAZ) was in the middle of the cross section of the specimens. By this all parallel situated structure areas were loaded by the same total strain. Figure 4 shows the results obtained: The specimens from the weld material as well as those from the HAZ behaved like those from the base metal.

Influence of As-Cast Surfaces

Since the inner surface of cast steel casings often remain in the as-cast condition, the question arose as to the influence of such surfaces on the low cycle fatigue behaviour. Figure 5 gives the results of flat specimens of the 1%CrMoV cast steel type GS-17 CrMoV 5 11, which were tested with machined and as-cast surfaces. In tests at room temperature the as-cast surface gave a reduction of the number of cycles to crack initiation, but not so at higher temperature (here 530°C). The scale which is formed at elevated temperatures obviously has the same life time reducing effect as the as-cast surface for this grade of cast steel.

Behaviour of Notched Specimens

As is known from experience, cracks in cyclicly loaded components generally appear first in areas of design notches and natural defects. Therefore, the fatigue strain concentration factor $K_{f\varepsilon}$ should be determined under cycles similar to those under service conditions. Such investigations are not yet available in the literature [6] and [7]. Figure 6 contains the results, found in a comparison investigation with strain controlled tests of smooth specimens and stress controlled tests of notched (v-notch, $K_t = 4.2$) specimens of cast steel type GS-22 Mo 4. The evaluation was performed by comparing the numbers of cycles to crack initiation. Remarkable is the unexpectedly steep increase of $K_{f\varepsilon}$ especially under cycles with a hold time at very low nominal stress ranges. Therefore, it must still be proven, whether stress controlled tests with notched specimens are generally qualified for the determination of the strain range amplitudes at elevated temperatures, because of possible effects of high-temperature creep. Well defined results are obviously only to be found if testing techniques are used which allow the control of constant strain amplitudes in the notch root and the exact measuring of crack initiation.

Low Cycle Fatigue Tests with Simultaneous Cycling of Strain and Temperature

Figure 7 gives the first results, obtained with 1%CrMoV forged steel type 21 CrMoV 5 11. It is evident that specimens loaded with simultaneously cycling temperatures and strains (shearstrains) endure for a higher number of cycles to crack initiation than those specimens which are tested at a constant upper limit temperature. (The same result was found for a heat resistant nickel base alloy). This is in contradiction to i.e. Udoguchi and Wada [8] as well as Nippes and Uy [9], who found a less favourable behaviour in push-pull tests under simultaneously cycling strain and temperature than in isothermal low cycle fatigue tests at the maximum temperature of their respective cycles. Since in such combined push-pull tests the thermal expansion of the specimen is difficult to compensate, there remains some doubt as to the actual loading conditions of such tests.

SUMMARY AND CONCLUSION

The results obtained here allow a more exact statement about permissible temperature differences in turbine components than those investigations available in the literature, since test conditions were very closely adjusted to the actual service loading conditions of such components.

In addition, tests under simultaneous strain-temperature cycling conditions revealed a more favourable material behaviour than under isothermal strain-cycling at the constant maximum temperature of the same temperature range. This means, that results from isothermal low-cycle fatigue tests may be safely applied for design calculations even for cyclic temperature loading conditions, if the calculation is based on the material's low-cycle fatigue behaviour at the maximum temperature of the cycle.

Many points are still open for investigation. For example, Sautter [2] studied possible relations between results from creep-rupture tests and hold-time low-cycle fatigue tests, performed at the same temperature up to lifetimes of about 100 h (Figure 8). He found a method for correlation, which, however, has to be confirmed as soon as the results of hold-time low-cycle fatigue tests with up to 10^4 cycles to crack initiation become available. Appropriate long-time low-cycle fatigue tests are now being performed, with intensive studies on possible creep-rupture/low-cycle-fatigue interrelations.

Further research work is concentrated on 400 mm dia.-turbine shaft models with circumferential notches of different geometries, which are fatigue strained by controlled external induction hearing, in order to study the effects of hold times, notches and component size.

Additional efforts are necessary in the field of damage accumulation methods for random low-cycle fatigue straining and temperature cycling conditions, since the Palmgren-Miner-rule obviously does not give a sufficiently precise description of the effects of those strain-time-temperature cycles occurring during turbine operation. Appropriate tests with a combination of cycles of different severity are being prepared.

In Germany, the different problems mentioned above are being treated in joint industry and university test programs with close cooperation and appropriate timing among all parties involved.

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Table 1 Chemical Composition in %

Material	C	Si	Mn	P	S	Cr	Mo	Ni	V
14 MoV 6 3	.16	.23	.54	.024	.006	.44	.58	-	.28
13 CrMo 4 4	.14	.27	.40	.015	.021	.95	.42	-	-
21 CrMoV 5 11	.21	.37	.49	.020	.025	1.40	1.03	.25	.30
GS-22 Mo 4	.23	.46	.64	.015	.008	.13	.39	.16	-
GS-17 CrMoV 5 11	.18	.43	.62	.011	.012	1.31	.92	.12	.24
weld metal	.06	.51	1.18	.030	.011	1.10	1.15	.02	.24
GS-X 22 CrMoV 12 1	.24	.24	.49	.025	0.13	11.41	1.02	.79	.26

Table 2 Quality Heat Treatment and Mechanical Properties

Material	Quality Heat Treatment	T °C	R_m N/mm²	$R_{p0.2}$ N/mm²	A %	Z %	Impact Test ISO-V (DVM) J
14 MoV 6 3	quenched and tempered	Rt 530	587 394	405 253	25 59	66 76	(63) -
13 CrMo 4 4	quenched and tempered	Rt 530	485 375	314 173	31 37	65 79	(161) -
21 CrMoV 5 11	940°C/oil, 720°C/air	Rt 530 600	783 534 443	656 460 400	20 25 27	68 78 84	172 -
GS-22 Mo 4	950°C/air, 700°C/furnace	Rt 530	509 323	305 176	27 37	59 75	(70)
GS-17 CrMoV 5 11 weldment*)	950°C 12h/oil, 720°C 12h/furnace + 720°C 12h/furnace 730°C 1h/air	Rt 530 Rt	647 445 635	506 407 381	22 19 24	69 71 71	92 - 101
G-X 22 CrMoV 12 1	1050°C/air, 720°C/furnace	Rt 530	842 508	652 357	17 24	40 43	31 -

*)electrode Hera CrMoV 3

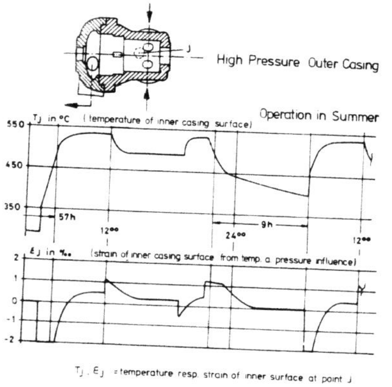
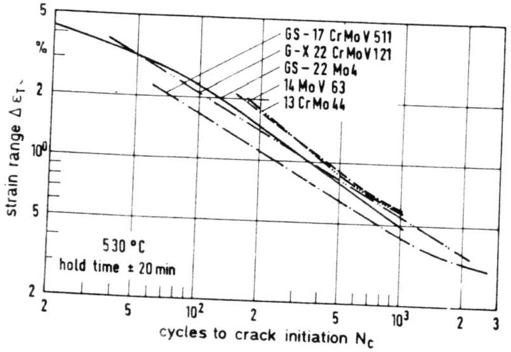


Figure 1



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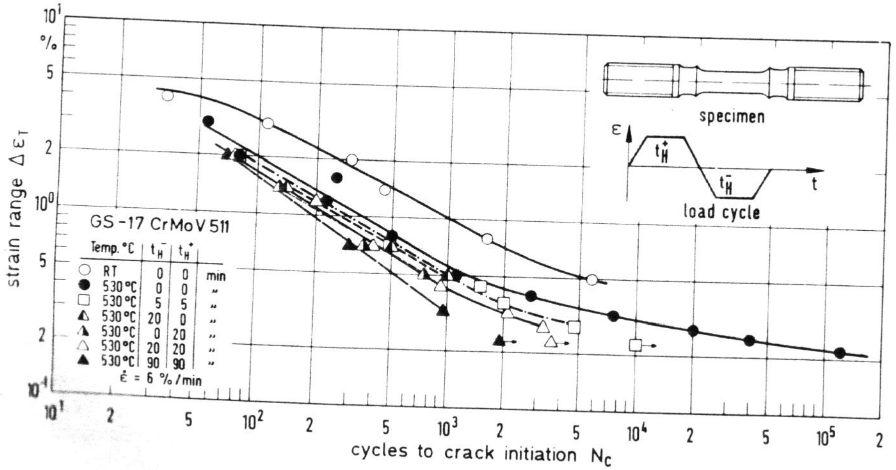
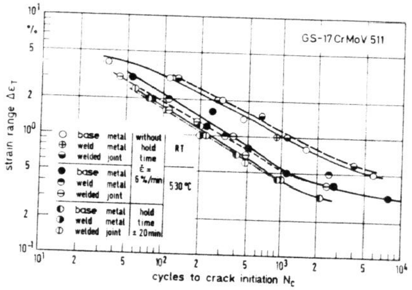


Figure 3



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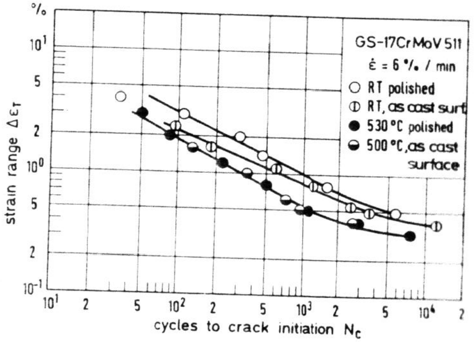

Figure 5

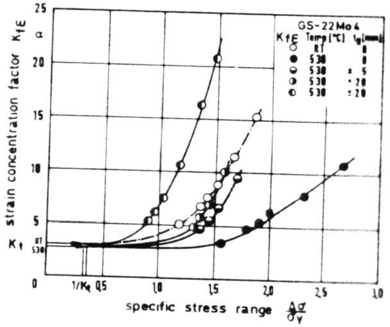

Figure 6

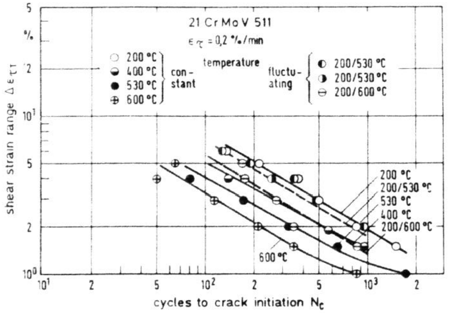

Figure 7

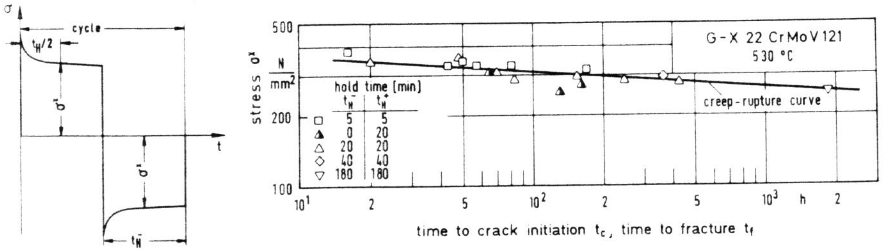

Figure 8