SIMULATION OF THE SERVICE CONDITIONS OF HEAT RESISTANT STEELS BY CREEP-RUPTURE TESTS UNDER VARIABLE STRESS OR TEMPERATURE AND BY STRAIN CONTROLLED SERVICE-TYPE FATIGUE TESTS

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ABSTRACT

To simulate the cyclical creep conditions, creep-rupture tests of up to 20 000 h under rectangular cyclically changed stress or temperature were carried out for six heat resistant steels with a low number of cycles to rupture. The resultant life under cyclically changed stress or temperature was found to be markedly shorter than that calculated according to the life fraction rule, and dependent on the various parameters of the rectangular cycle. The life fraction rule modified by constants can be used for design purposes.

To simulate the service conditions at the heated surfaces of heavy components where creep-fatigue interaction occurs, a test programme comprising strain controlled anisothermal service-type cycles, comparable isothermal cycles and similar tests comprising packages of strain cycles alternating with packages of creep steps was established. The results obtained to date indicate that package-type testing produces good agreement with comparable continuous cycling. An evaluation of the test results on the basis of the generalised damage accumulation rule revealed a wide scatter of relative life values centered on a value below unity.

KEYWORDS

Creep-rupture under variable conditions, heat resistant steels, modified life fraction rule, strain controlled service-type cycles, creep-fatigue interaction, generalised damage accumulation rule.

INTRODUCTION

High-temperature machines and plants are generally operated with cyclically changing power. At the heated surfaces of heavy components, these cyclical changes lead to temperature transients and thus strain cycles such as are schematically shown in Fig. 1. A simplification thereof leads to schematic strain cycles of the type illustrated in Fig. 2, that is, to service-type strain controlled tests. When the strain ranges become small, as is to be expected under long-term loadings, alternating strain approximates variable creep conditions.

SIMULATION OF VARIABLE CREEP-RUPTURE CONDITIONS

Creep-Rupture Testing under variable Stress or Temperature

Many service-type loading cycles, including that shown in Fig. 2, can be approximately described as rectangular cycles. This form of cycle was therefore selected for creep-rupture testing under variable stress or temperature, whereby the cycle parameters were varied over a wide range (Fig. 3).

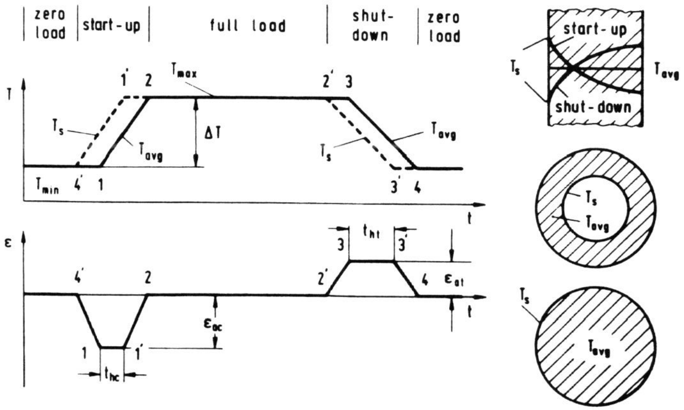


Fig. 1. Course of temperature T and resultant total strain ε versus time t during a service cycle of a heavy component.

The creep-rupture tests were carried out as interrupted tests. Multi-specimen machines were used for time intervals of more than about 100 h. In such cases, the test machine was changed to vary the temperature, and the specimen string was changed to vary the stress. In all tests, only time under stress and temperature contributed to the rupture time. The tests were carried out with the six typical heat resistant steels shown in Table 1, whereby the specimens were in each case taken from one heat of the steel in question. The chemical composition, heat treatment and mechanical properties of the tested steels were within the usual ranges. Details of the test method and test materials were published earlier (Wiegand, Granacher and Sander, 1975).

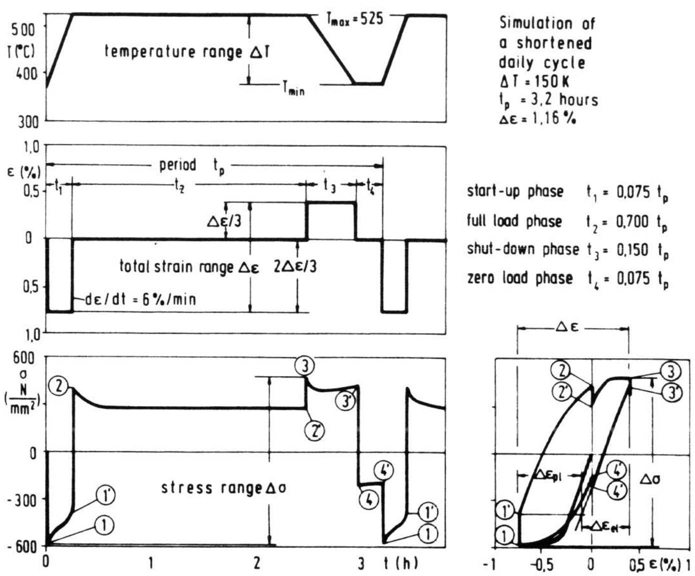
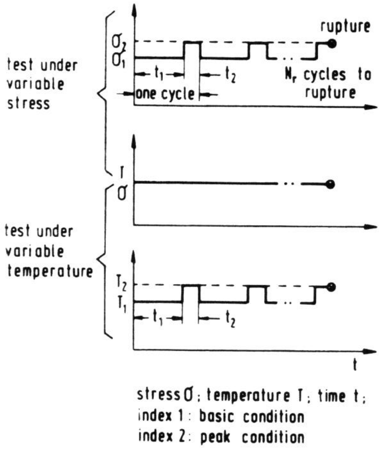


Fig. 2. Example of an anisothermal strain controlled service-type test cycle and course of resultant stress σ for a 1 Cr-Mo-Ni-V turbine rotor steel.



stress σ; temperature T; time t;
index 1: basic condition
index 2: peak condition

variable	symbol and definition	range
peak time proportion	$x = \frac{100 \cdot t_2}{t_1 + t_2}$	3,10,30,80 %
stress change	$q_\sigma = \frac{100(\sigma_2 - \sigma_1)}{\sigma_1}$	25,60,100 %
temperature change	$\Delta T = T_2 - T_1$	25,50,75 or 100K
limiting rupture time	$t_{r1} = f(T_1, \sigma_1)$ $t_{r2} = f(T_2, \sigma_2)$	10 to 10^6 h
number of cycles to rupture	N_r	3 to 30 cycles
rupture time under variable conditions	measured: t_{rv}	100 to 20000 h
	life fraction rule: $t_{rv}' = \frac{t_{r1} \cdot t_{r2}}{t_{r2} + x(t_{r1} - t_{r2})}$	
relative life	$L_t = \sum t / t_r = t_{rv} / t_{rv}'$	

Fig. 3. Creep-rupture testing under rectangular cyclical stress or temperature.

TABLE 1 Steels tested under cyclical Creep Conditions and Material Factors L_{SM}, L_{TM} of a factoral Concept for the mean relative Life

Type of steel	0.3Mo	2.3Cr-1Mo	1Cr-1Mo-0.3V	1Cr-1Mo-0.3V, cast	12Cr-1Mo-V	17Cr-13Ni-1Mo
L_{SM}	1.03	0.88	1.12	1.03	1.22	0.85
L_{TM}	0.92	0.94	1.19	0.99	1.01	0.89

There are different rules, some of them complicated, for describing variable creep rupture behaviour. The most of them were summarised by Manson and Brown (1958) and van Leeuwen (1965). Widely used because it is simple to apply is the life fraction rule $\sum t/t_r = 1$. According to this rule, time intervals under constant conditions leading to rupture times t_r are to be accumulated. Rupture occurs when the critical value 1 is reached. When one compares the actual rupture times t_{rv} found in the tests with those calculated according to the life fraction rule t_{rv}' (Fig. 4), one finds the former to be notably shorter than the latter. So one can define the relative life as $L_t = t_{rv}/t_{rv}'$. Variable stress reduces the relative life of a steel more than variable temperature, but the reduction does not depend on the time to rupture. An obvious course is therefore to apply the life fraction rule in the form proposed by Mordfin, Halsey and Green (1959), $\sum t/t_r = L_{tm}$, with the mean relative life L_{tm} as a constant. This constant can be determined via the distribution of relative life L_t from a series of tests. For the range of parameters covered by the tests, the mean relative life can be estimated as the geometrical mean of the distribution of relative life, and the confidence limits of the mean and 95% limits of the distribution can be calculated (Kloos, Granacher and Abelt, 1978). If one then summarises the test results for all steels, one finds a mean relative life $L_{tSm} = 0.65$ for variable stress and $L_{tTm} = 0.85$ for variable temperature.

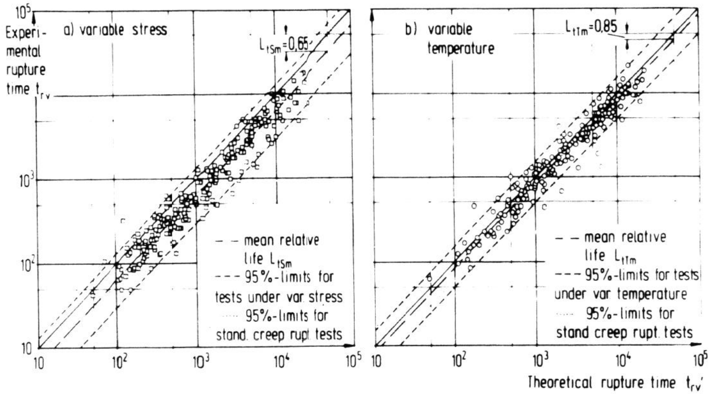


Fig. 4. Experimental rupture time over theoretical rupture time according to the life fraction rule for all tests on the six steels in Table 1 and according to the test programme in Fig. 3.

Parameters influencing the mean relative Life of the modified Life Fraction Rule

Further parameters that influence the mean relative life were sought to reduce the scatter shown in Fig. 4.

For all experiments, four ranges were defined and separately evaluated to access the influence of the level and rupture time of the basic condition (σ_1, T_1, t_{r1}). The distribution of the relative life values are shown as a bar graph in Fig. 5. After making allowances for the confidence limits, both for variable stress and variable temperature, one finds no great difference between the individual ranges in respect of mean relative life. The difference between range 2, that which is mainly important in practice, and the mean value for all four ranges is relatively small. When one compares the distribution of the tests under variable conditions and the distribution of the standard creep-rupture tests conducted on the same heats, one notes the markedly shorter life and the greater scatter of the results obtained under variable conditions.

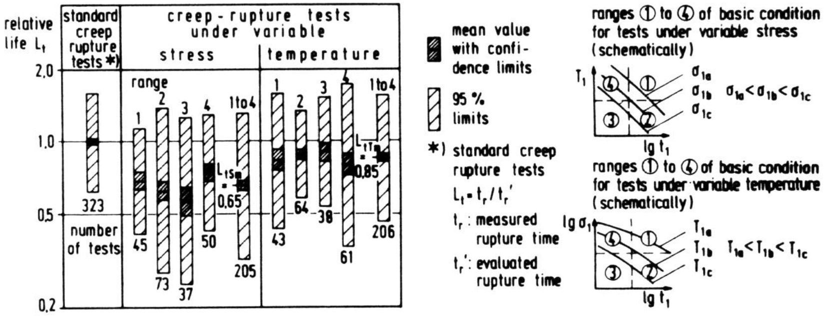


Fig. 5. Influence of the basic condition on the mean relative life for all tests on the six steels in Table 1 and according to the test programme in Fig. 3.

When one summarises the results of all tests for the different types of steel, one finds that the individual steels have markedly differing mean relative lives for variable stress and variable temperature, as shown in Fig. 6. One can therefore define the material factors L_{SM} and L_{TM} for the influence of the types of steel shown in Table 1.

The dependence of mean relative life on the so-called cycle parameters peak time proportion x and stress change q_σ or temperature change ΔT as established in all tests is shown in Fig. 7.

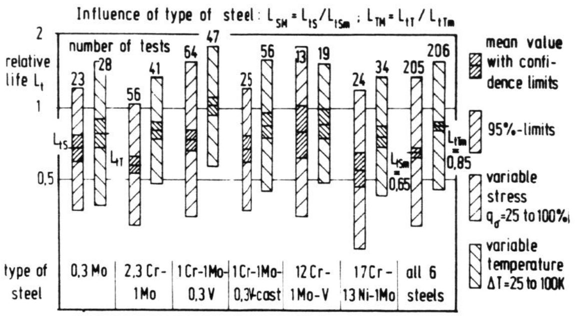


Fig. 6. Influence of the type of steel on mean relative life (all tests according to test programme in Fig. 3).

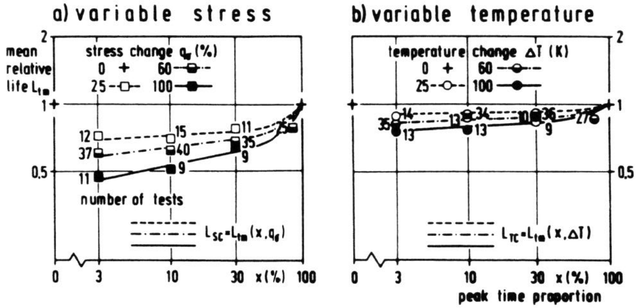


Fig. 7. Influence of the cycle parameters on mean relative life (all tests on the six steels in Table 1 and according to the test programme in Fig. 3).

The dependence which was found for the materials as a group was confirmed by the tendencies in the behaviours of the individual steels. The cycle factors L_{SC} and L_{TC} are therefore as shown in Table 2.

All remarks until now concerned tests conducted according to Fig. 3, with cycles beginning with the basic condition.

TABLE 2 Cycle Factors L_{SC} and L_{TC} of a factoral Concept for relative Life

x	L_{SC}				L_{TC}		
%	q_σ (%) =	25	60	100	ΔT (K) =	25	50	100
3		0.69	0.58	0.45		0.88	0.82	0.76
10		0.72	0.64	0.53		0.89	0.84	0.79
30		0.75	0.70	0.62		0.90	0.86	0.82
80		0.84	0.80	0.74		0.93	0.90	0.88

Tests under the same conditions but with cycles that begin with the peak condition were also carried out. The ratio between rupture time with cycles beginning with a peak condition $t_{rv\,2\,1}$ and rupture time with cycles beginning with a basic condition t_{rv} led to a distribution whose geometrical mean defines a sequential factor L_{SS} or L_{TS} (Fig. 8).

According to the results obtained until now, the mean relative life with cycles beginning with a peak condition is more likely to be shorter, especially when the temperature is varied.

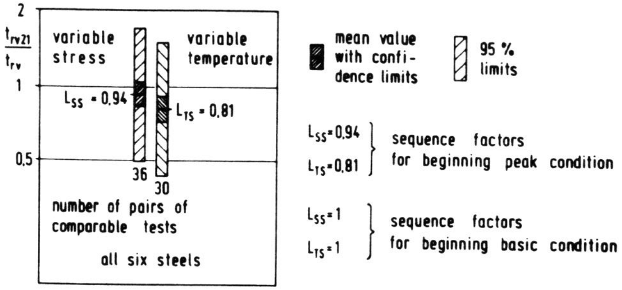


Fig. 8. Influence of the sequence of basic and peak condition within the cycle on mean relative life.

The modified Life Fraction Rule in Application

Various concepts for the derivation of the mean relative life to allow application of the modified life fraction rule can be developed. The simplest but also least accurate of these is the "one-value-concept", for which one can derive a constant $L_m = 0.77$ from all test results. When one allows for the influence of the sequence of loadings in the cycle and the nature of change, one arrives at a "four-value-concept" for computing the mean relative life. Within a wide range of cycle parameters and for steels of the types investigated, one can state a mean value of $L_{tSm} = 0.65$ (0.61) for changing stress and $L_{tTm} = 0.85$ (0.69) for changing temperature, whereby the values in parentheses are for cycles beginnig with the peak condition. Finally, there is a "factoral-concept" which also allows for differing material behaviour and the influence of the cycle parameters. It can be expressed in the form of $L_{tSm} = L_{SM} \cdot L_{SC} \cdot L_{SS}$ or $L_{tTm} = L_{TM} \cdot L_{TC} \cdot L_{TS}$, with the material factors L_{SM} and L_{TM} from Table 1, the cycle factors L_{SC} and L_{TC} from Table 2 and the sequential factors L_{SS} and L_{TS} from Fig. 8. Fig. 9 shows the distribution of measured rupture time over calculated rupture time for all tests, the calculations having been carried out according to the modified life fraction rule with the three different concepts for mean relative life mentioned above. One notes that use of the factoral-concept leads to a distribution mean of almost unity, whereby the 95%-limits of the standard creep-rupture test are no longer greatly exceeded. One can therefore say that more complicated rules do not appear to offer advantages over the modified life fraction rule with an experimentally determined mean relative life when design data concerning creep-rupture are needed.

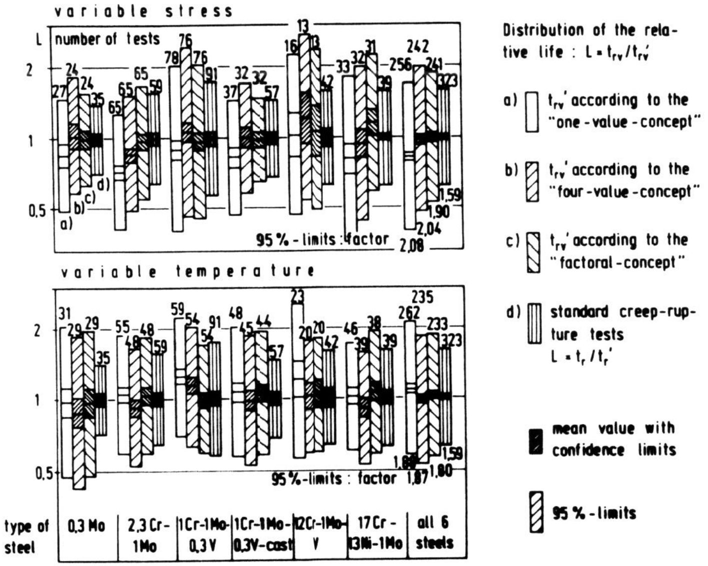


Fig. 9. Distribution of measured rupture time over expected rupture time for creep rupture tests under rectangular cyclical stress or temperature and for standard creep-rupture tests.

For design purposes, the factoral-concept can be recommended, when the design data agree with the investigated cycles and materials. This concept is relative to mean values. When it is used for minimum values, these are to be reduced by about 15% regarding the larger scatter band under variable conditions. If a material is only roughly comparable with those investigated until now, the four-value-concept is more recommendable, whereby the minimum values must be reduced by about 20%. When the number of cycles exceeds greatly the range observed (3 to 30) with both these concepts, one should use the smaller L_{tm} value which was calculated for the reverse sequence. In both concepts a value $t_{rv}' = t_{r2}$ can be assumed when x is close to 100% and the modified life fraction rule produces a value of $t_{rv}' < t_{r2}$.

Other problems that have yet to be investigated concern the influence of higher number of cycles and more complicated loading cycles, particularly those with simultaneous changes in strain and temperature, creep behaviour under variable conditions and the question of whether the behaviour found for individual heats is typical of the types of steel in question.

SIMULATION OF SERVICE-TYPE STRAIN CYCLING

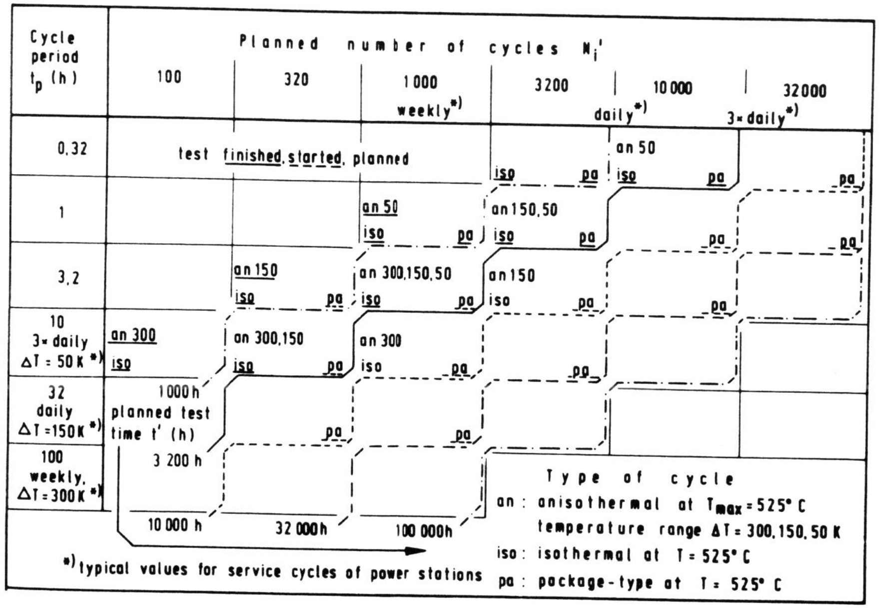
Service-Type Strain controlled Fatigue Tests

In the case of creep and high strain fatigue interaction, strain controlled tests are necessary to gain design data (Timo, 1967, 1971; Schinn and Schieferstein, 1970). Of special interest is the simulation of the loading cycle at the heated surface of heavy components, as shown in Fig. 2. Usually, this cycle is tested by isothermal high strain fatigue with compressive and tensile hold times only. A number of problems arise in applying the results of such conventional fatigue tests: extrapolation to considerable longer hold times is normally necessary, and assumptions must be made concerning the effects of the full-load phase with a total strain of zero. Ignoring this phase can lead to an over-estimation of the component's design life, whilst taking this phase into account in the sum of compressive and tensile hold times can produce too conservative results. Another problem results from the anisothermal nature of the service-type cycle. Some investigators (Udoguchi, 1971; Lindholm and Davidson, 1973) found that simulation by isothermal testing does not necessarily lead to conservative results, even if the tests are carried out at the highest cycle temperature.

It is therefore a need to verify the effects of service-type strain cycling by special tests. Table 3 shows standardised loading cycles of the type described in Fig. 2. To abbreviate the tests, the cycle periods were shortened and the strain ranges were increased. Anisothermal cycles and comparable isothermal cycles are planned for longest test times of about 3 000 to 10 000 h. The isothermal cycles are tested at the highest temperature (T = 525 °C) of the anisothermal cycles. In the anisothermal tests, the thermal strain due to the course of test temperature is fully compensated. Test temperature and total axial strain are therefore independent test parameters in the servohydraulic test machine used.

Test times of about 30 000 h are provided for by the so-called package-type tests. These tests are carried out isothermally at 525 °C, in about 10 "test packages", following the pattern shown in Fig. 10. Each test package comprises a strain cycling package and a creep testing package. In the strain cycling package the service-cycle period is 0.1 h. This allows for the first part of relaxation in the service-type cycles. At the end of each strain cycling package, at least one complete cycle giving the "equivalent creep stresses" σ_{h2} and σ_{h3} according to the life fraction rule is carried out. The rests of the hold times (t_{h2}, t_{h3}) neglected in the strain cycling package are tested in the subsequent creep package, carried out in a creep testing machine with the stresses σ_{h2} and σ_{h3}. In this manner, the relaxation strain not covered by the strain cycling package is approximated by creep strain. A plastic strain reverse closes the hysteresis loop at the beginning of the following strain cycling package.

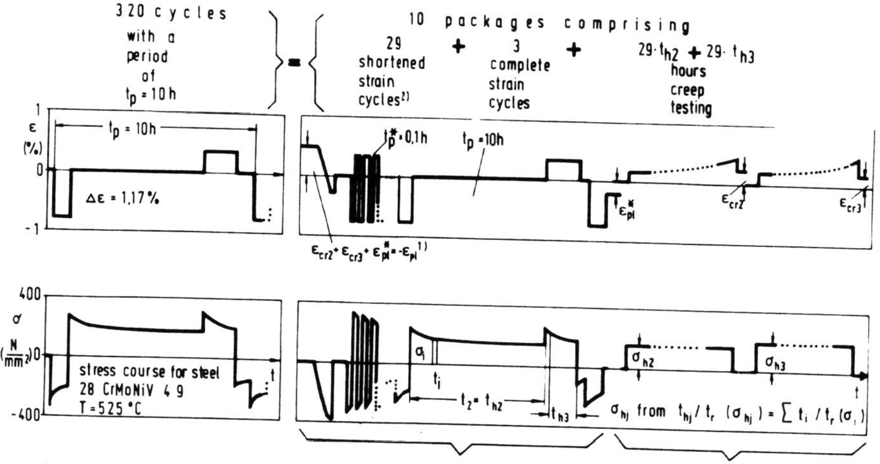
TABLE 3 Test Programme developed for Service-Type Strain Cycles



Cycle period t_p (h)	Planned number of cycles N_i' 100	320	1 000 weekly*)	3200	10 000 daily*)	32000 3× daily*)
0,32	test finished, started, planned			iso pa	an 50 iso pa	pa
1			an 50 iso pa	an 150,50 iso pa	pa	pa
3,2		an 150 iso pa	an 300,150,50 iso pa	an 150 iso pa	pa	
10 3× daily ΔT = 50 K *)	an 300 iso	an 300,150 iso pa	an 300 iso pa	pa		
32 daily ΔT = 150 K *)	1000 h planned test time t' (h)	pa	pa			
100 weekly, ΔT = 300 K *)	3 200 h					
	10 000 h	32 000h	100 000h			

*) typical values for service cycles of power stations

Type of cycle
an : anisothermal at $T_{max} = 525°$ C temperature range $\Delta T = 300, 150, 50$ K
iso : isothermal at T = 525° C
pa : package-type at T = 525° C



3200h service-type testing = 329h strain controlled fatigue testing + 2451h tension creep testing 3)

1) plastic strain reverse ε_{pl}, not within the first package
2) within the first package first three cycles being complete cycles
3) 420h compression creep testing being omitted and partly replaced by plastic strain reverse 1)

Fig. 10. Package-type tests for the simulation of isothermal long-term service-type loading.

Fatigue Life in the Strain controlled Tests

The service-type tests were carried out on a 1 Cr-Mo-Ni-V turbine rotor steel. The specimens (10 mm diameter, about 35 mm gauge length) were taken longitudinally from the peripheral zone of a 400 mm-diameter forged shaft with upper bainite structure. In the tests, the number of cycles to crack initiation N_i was defined by a 2% drop of the tensile stress amplitude below the rectilinear relation between this amplitude and the number of cycles. This corresponds with a crack depth of about 0. 5 mm.

The results of the tests according to Table 3 that have been carried out until now are listed in Table 4.

TABLE 4 Results of Service-Type Tests on 1Cr-Mo-Ni-V Steel

Cycle period t_p, planned number of cycles N_i' and planned test time t'			Temperature range ΔT, total strain range Δε and measured number of cycles to crack initiation N_i Anisothermal tests (T_{max}=525 °C)			Isothermal tests at 525 °C		Package-type tests at 525 °C	
t_p h	N_i'	t' h	ΔT °C	Δε %	N_i	Δε %	N_i	Δε %	N_i
0. 32	10 000	3 200				0. 43	2 625	0. 43	2 850
0. 32	3 200	1 000				0. 52	1 305	0. 53	1 280
1. 00	1 000	1 000	50	0. 74	606	0. 73	450	0. 74	475
1. 00	1 000	1 000						0. 74	400
1. 00	3 200					0. 53	1 103	0. 53	1 040
3. 20	320	1 000	150	1. 16	328	1. 20	260		
3. 20	1 000	3 200				0. 74	363		
10. 00	100	1 000	300	2. 43	57	2. 45	83		

The results of comparable tests of a different type are plotted in Fig. 11. If one proceeds from the anisothermal tests to the comparable isothermal tests (Fig. 11a), one notes a reduction in the number of cycles to crack initiation when the smaller strain ranges are observed. Estimates of the anisothermal fatigue behaviour based on isothermal tests therefore lead to a conservative number of cycles to crack initiation in the observed range of parameters. Conventional hold time tests had already proven this for comparable steels (Ewald and others, 1977; Bhongbhibhat, 1979). Conventional hold time tests with the same sum of tensile and compression hold times as isothermal service-type tests ($t_{hc} + t_{ht} = t_1 + t_3$) produce higher numbers of cycles to crack initiation (Fig. 11b) and therefore lead to unconservative results. There is a relatively good agreement (Fig. 11c) between the results of the isothermal service-type tests and the comparable package-type tests. This confirms the possibility of carrying out long-term service-type tests utilising servohydraulic machines for only short times. All statements made up to this point are based on relatively few short-

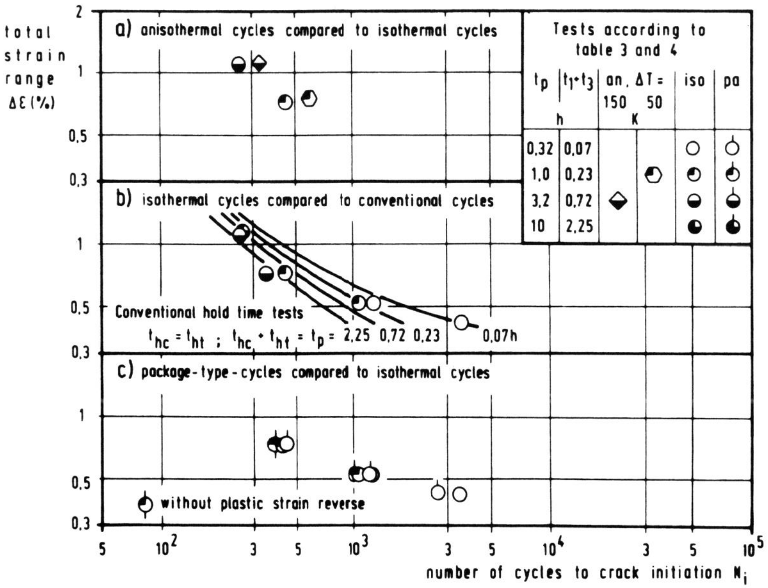


Fig. 11. Comparable results of service-type tests and conventional hold-time tests on the same heat of the 1Cr-Mo-Ni-V steel, conducted partly by Bhongbhibhat (1979).

term tests extending to about 2 000 h. The long-term tests as shown in Table 3 have been started, to confirm the statements for the lower strain ranges that are relevant in practice.

Damage Accumulation in Creep-Fatigue Interaction

A life analysis is needed if the test results are to be applied to other load cycles. In view of the long-term behaviour, the main interest is in the generalised damage accumulation rule $L_N + L_t = L$ with the relative fatigue life $L_N = \sum N/N_i$ and the relative creep-rupture life L_t according to the modified life fraction rule (Taira, 1962; Sunamoto, Endo and Fujihara, 1973; Sidey, 1977; Batte, Murphy and Stringer, 1978).

A problem in the use of this rule consists of the partition of damage into a fatigue portion and a creep portion. The plastic relaxation strain during the hold times shows strain rates that decrease rapidly with time. One can therefore regard an initial part of this strain as cyclical plastic strain. A reference fatigue curve for a period of 0.1 h was used in the determination of the relative fatigue life. For the determination of the relative creep-rupture life the dependance of the stress amplitudes on the number of cycles and on the time within the hold phases was considered. As a result, the relative creep-rupture life is plotted against the corresponding relative fatigue life in Fig. 12. The life analysis reveals a relatively broad scatter of the test results about a line corresponding to a total life L that is a little smaller than unity. This distribution also agrees with the results of the creep-rupture tests under rectangular cyclically-changed stress conducted with a 1Cr-Mo-V steel (Fig. 6).

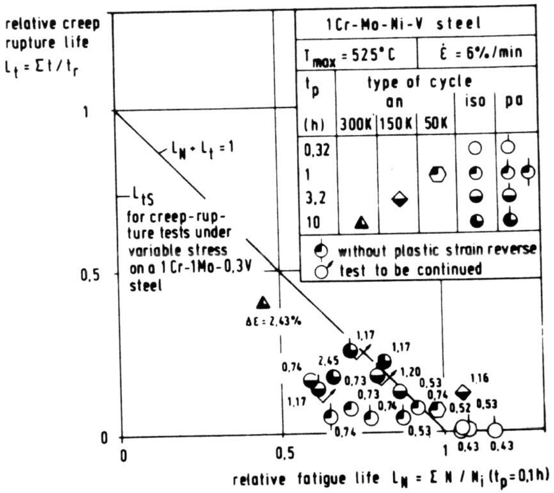


Fig. 12. Evaluation of the test results of Table 4 on the basis of the generalised damage accumulation rule.

This life analysis verifies the generalised damage accumulation rule relatively well. Use of this rule in the way shown above however necessitates a cycle-dependent construction of the hysteresis loop. The object of further research work is therefore to determine how and to what extent the accumulated damage and the position of a hold phase within a cycle will influence the plastic and relaxation behaviour and the reference fatigue curves and creep-rupture curves.

Additional information concerning the failure mechanism can be obtained by metallographical examination. The study of failed specimens in the scanning electron microscope revealed that crack initiation was mainly effected by corrosion, with a transgranular mode of crack propagation. Some specimens also showed creep-induced micrcracks indicating a creep-induced damage portion.

CONCLUSIONS

The modified life fraction rule with experimentally determined constants is useful in designing against creep-rupture under cyclically varied stress or temperature. This statement is the result of extended tests on six typical heat resistant steels.

The long-term service-type strain cycling of a 1 Cr-Mo-Ni-V steel can be simulated by package-type tests with shortened strain cycles and extended creep testing. The creep-fatigue interaction can be analysed with the generalised damage accumulation rule.

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