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CREEP FATIGUE, PART I: Compilation of Data and Trends in the Creep-Fatigue Behavior of Low Alloy Steels

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PAPER I
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ABSTRACT

This paper describes an attempt to compile the creep-fatigue data of low alloy steels. In part I, international data have been collected to compare the variability that exists in a particular low alloy steel when characterized in different laboratories. From this work of compilation, trends in the creep-fatigue behavior of low alloy steels have been identified in Part II of this paper and a review of life prediction methods and assessments will be discussed in subsequent papers. The creep-fatigue behavior, in general, improved with the increase in chromium content; however, when additional alloying elements were added to a standard alloy system, the creep-fatigue behavior of that alloy deteriorated. There was a threshold temperature limit as well as a threshold hold time beyond which only interactions of creep-fatigue and oxidation occurred and reduced the life considerably. However, limiting values of threshold temperature and hold times for different low alloy steels have not yet been determined.

KEY WORDS

low alloy steels, hold times, N&T heat treatment, total strain range, test temperature, creep-fatigue.

PART I:
COMPILATION OF CREEP-FATIGUE DATA

Introduction

Creep-fatigue data of low alloy steels are of considerable importance, since they are used in the design of power plant components and in predicting their life span. Much of these data are not in the public domain and remain classified. Attempts have been made to search the literature and compile a data bank from the published sources. This effort is purely for the purpose of identifying trends in creep-fatigue behavior, life prediction methods and assessing the data with the modified Diercks equation.

In order to identify a particular low alloy steel and its creep-fatigue data, low alloy steels are classified in the order of their chromium content. Hence, there are 0.5Cr-Mo-V, 1Cr-Mo-V, 1.25Cr-Mo, 2.25Cr-Mo, 2.25Cr-Mo-V and 9Cr-1Mo steels. There are several batches in each of these low alloy steel grades. thus, "batch" is used primarily to identify a particular low alloy steel grade and its source where characterized.

Before these data can be used, the reader is informed about the "variability" that exists among various batches of a particular low alloy steel. The possibilities are as follows:

1. Differences in the specimen geometry and orientation.
2. Differences in extensometry, variability between longitudinal and diametral strains.
3. Differences in material composition.
4. Differences in a particular heat treatment:
    a) heating and cooling rates,
    b) cooling media,
    c) higher and lower temperature ranges, and
    d) time of hold at a specified temperature.
5. Differences in microstructure.
6. Differences in material production routes (conventional versus advanced methods).
7. Differences in test parameters:
    a) temperature differences,
    b) differences in strain rate,
    c) type of heating (e.g., induction and resistance), and
    d) test interruptions.
8. Differences in the material production form such as casting and forging.
9. Differences in failure criteria.

In addition to the above possibilities there is also variability associated with the international data itself. Hence, a lot of care is needed while using these data. This compilation effort may provide some future directions in the generation of creep-fatigue data, since there is no standard of practice for conducting such complex tests.

Data Collection

Creep-fatigue data from various international societies, laboratories, universities and private research institutions have been collected. In order to identify data against each other, they have been represented in "batches" within a steel grade. Data sources have been duly referenced. Table 1 lists the low alloy steel types, material conditions, and sources with the details of the test parameters.

Table 1
Summary of the creep-fatigue data compiled

Alloy Type	Batch	Source	Heat Treatment	Test Temperature	Reference
.5Cr-Mo-V	1	CEGB	N&T	550°C	1
1Cr-Mo-V	1	NASA	N&T	540°C	2
	1	NASA	-do-	485°C	2
	2	G.E. Company	-do-	538°C	3
	2	-do-	-do-	483°C	3
	3	B.B. Company	Hot rolled	550°C	4
	4	Bristol Univ.	Forged N&T	565°C	5-6
	5	CEGB	Forged N&T	550°C	1
1.25Cr-Mo	1	Elcom. Victoria	As received	550°C	7
	2	N.I.of Metals Japan	N&T	600°C	8
2.25Cr-Mo	1	NASA	Annealed	540°C	2
	1	-do-	N&T	-do-	2
	1	-do-	Q&T	485°C	2
	2	G.E. Company	Annealed	538°C	3
	2	-do-	N&T	538°C	3
	2	-do-	Q&T	483°C	3
	3	J.S.M.S.	N&T	600°C	9
	4	O.R.N.L.	N&T	502°C	10
	5	M.H.Eng.	N&T	600°C	11
	6	European Communities	N&T	550°C	12
	7	University of Connecticut	N&T	593°C	13
	8	-do-	N&T	593°C	13
9Cr-1Mo	1	University of Bristol	N&T	550°C	14
	2	O.R.N.L.	N&T	538°C	15

In several cases the heat treatments within a type, e.g., N&T, were unspecified. Those salient features are identified for all the batches, tabulated in Tables 2 and 3 respectively.

Table 2

Summary of salient features of the compiled data

1/2Cr-Mo-V Steel					
Batch	Source	Data Type	Heat Treatment	Salient Feature	Temp. °C
1	CEGB	0.5, 2 and 16 hrs tensile dwells	N&T	Unknown composition and stress range	550
1Cr-Mo-V Steel					
Batch	Source	Data Type	Heat Treatment	Salient Feature	Temp. °C
1	NASA	23 and 47 hrs. hold, Combined cycles (n).	N&T	Unknown composition and stress range	540 and 485
2	G.E.Co.	0/0, 23 and 47 hrs.(n).	N&T	-do-	538 and 483
3	B.B.& Co.	max. of 1/2 hr. unknown details	N&T	Unknown total strain range	550
4	Bristol University	0,1/2hr. t/0, t/t, 0/t & 18 hrs..	N&T	stress range is not known	565
5	CEGB	0.5, 2 and 16 hrs tensile dwell	N&T	heat treatment details unknown	550
1.25Cr-Mo Steel					
1	Electricity com. (V)	up to 10 min.	as received condition	Not heat treated as N&T.	550
2	NIM	up to 1 hr.	N&T	known details	600
2.25Cr-Mo Steel					
1	NASA	23 & 47 hrs.(n)	Annealed	unknown comp.	540
	NASA	23 & 47 hrs.(n)	N&T	-do-	540
	NASA	23 & 47 hrs.(n)	Q&T	-do-	485
2	G. E.Co.	0, 23 & 47hrs.n	Annealed	-do-	538
	G.E.Co.	0, 23 &47 hrs.n	N&T	-do-	538
	G.E.Co.	0. 23 &47 hrs.n	Q&T	-do-	483
3	J.S.M.	5 min. t/0, 0/t	N&T	only two tests	600
4	ORNL	6min. t/0, 0/t, t/t	N&T	one test each and large scatter	502
5	MHE Co.	up to 0.54 hr.	N&T	unknown comp.	600
6	European commis.	up to 10 min.	N&T	N&T conditions unknown	550
7	Connecticut, Univ.	0/0 data	N&T	no hold time tests	593
8 V containing	-do-	0/0 data, 2 frequencies	N&T	no hold time tests	593
9Cr-1Mo Steel					
1	Bristol Univ.	0/0 data	N&T	Unknown comp. and N&T cycle.	550
2	ORNL	0.25, 0.5 and 1 hr. tensile holds	N & T	Unknown comp. N&T details	538 & 593

It is evident from the above table that in several batches heat treatment temperature ranges and cooling details are not known. Available details have been tabulated together with the possible temperatures and cooling rates of the N&T condition in Table 3. These are compiled for 3 to 9% chromium steels in the ASTM data series publication DS 58 /16/ below. However, ASTM data series DS 58 also lacks the complete details.

Table 3

Summary of heat treatment parameters

Material	Batch	Heat Treatment Parameters
1Cr-Mo-V	1	Normalized from 855°C, tempered at 676°C, slowly furnace cooled (FC).
	4	Soaked at 1000°C, furnace cooled to 690°C at 50°C, held for 70 hrs. Air cooled (AC).
		Re-heated to 975°C and soaked in salt bath. Quenched into another salt bath at 450°C, AC.
		After rough machining, re-heated to 700°C for 20hrs. Prior to finish machining acts as tempering heat treatment and stress relieved.
1.25Cr-Mo	2	930°C/1.5 hrs. AC, 710°C/1.5 hrs. AC, 680°C / 1 hr. FC.
2.25Cr-Mo	1 &2	Annealed: 927°C/2hrs, 593°C AC to RT, rate unknown.
	1&2	N&T: 955°C/6hrs.AC, Tempering 705°C/6hrs. AC
	1&2	Q&T: 955°C/6hrs.WQ, Tempered 621°C/6hrs, AC
	3	N&T: 930°C/0.5 hr, AC, 690°C/1.5hrs, FC.
	4	N&T: 930°C/1hr. FC, 705°C/2hrs. slow cooling.
	5	N&T: 927°C/1hr.704 @0.33°Ch^{-1}, hold at 704°C for 2 hrs.,cool to RT @ 1.31°C/hr..
	7 &8	N&T: 955°C/1hr,AC, tempered at 730°C/2hrs AC
9Cr-Mo	ASTM DS 58	N&T: 900°C, tempered 671°C. Unknown soaking.

There are considerable variations between the normalizing and tempering temperatures. Periods of soaking and cooling rates for each grade of steel within the N&T condition are different. Types of cooling employed are furnace, air and water for the same heat treatment of the same low alloy steel grade. Thus the contribution of such variations to the creep-fatigue performance becomes an independent area to explore; besides, such effects have been isolated and ignored to identify trends in the creep-fatigue performance.

Summary of Mechanical Properties

Mechanical properties of various low alloy steels have been summarized in Table 4. Ductility has been calculated from the percentage reduction in area of a tensile test. Mechanical properties have been summarized from room and creep-fatigue test temperatures.

Table 4
Summary of mechanical properties

Material details (batch)	Yield strength MPa	Tensile strength MPa	% elongation	Ductility %
1Cr-Mo-V (1-2)	614.5[a], 454.75[b]	771.6[a], 502.28[b]	22.6[a], 25.5[b]	0.87[a], 1.77[b]
1Cr-Mo-V (3)	698[a]	797[a]	24[a]	1.17[a]
1Cr-Mo-V (4)	635[a], 400[b],300[c]	805[a], 500[c],420[b]	36[a], 40[b]	1.02[a], 1.6[b]
1.25Cr-Mo (1)	330[a],191[b]	534[a], 285[b]	29[a], 48[b]	1.3[a], 2.3[b]
2.25Cr-Mo(1-2)	261.82[a], 174.4[b]	516.8[a], 336.3[b]	32.7[a], 37[b]	1.11[a], 1.70[b]
N&T (1-2)	520.2[a], 400[b]	658[a], 461.7[b]	25[a], 21[b]	1.32[a], 1.51[b]
Q&T (1-2)	799.3[a], 620.1[b]	892.3[a], 689[b]	21.5[a], 19[b]	1.28[a], 1.30[b]
N&T (3)	369[a], 240[b]	549[a], 262[b]	34[a], 36[b]	1.51[a], 2.40[b]
N&T (6)	301[a], 500[b]	218[a], 336[b]	28.8[a], 33[b]	1.46[a], 1.68[b]
N&T (7)	470[a], 597[b]	305[a], 354[b]	20[a], 34.5[b]	1.5[a], 2.04[b]
N&T (8)	620[a], 443[b]	720[a], 456[b]	18[a], 26.5[b]	1.37[a] , 1.73[b]

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[a] Properties at room temperature

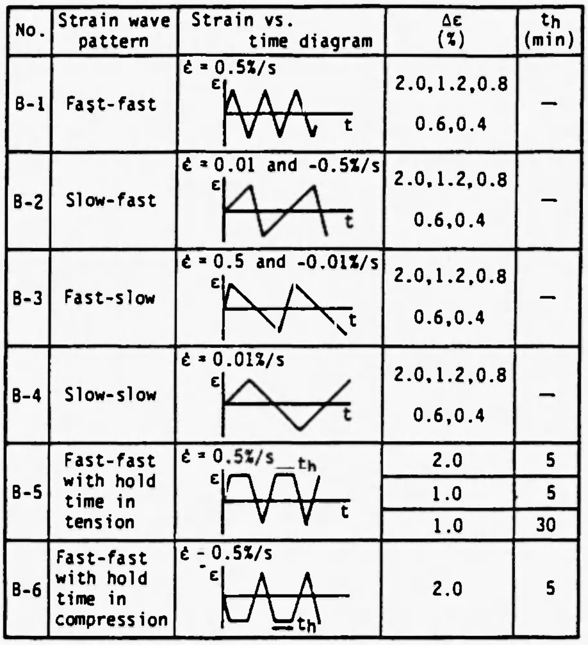
[b] Properties at creep-fatigue test temperature (ref. Table 1).

Creep-Fatigue Data

Several types of waveforms have been utilized around the world to generate creep-fatigue data. Some used ramp rates, others the hold time at the peak tensile or compressive halves. When hold time is the same in both directions, it is known as the balanced cycle (t/t); however, when it is different, the cycle is known as an unbalanced dwell cycle (xt/yt). In most cases the hold time was applied only in the tensile half (t/0) and compressive dwell tests (0/t) were conducted sparingly. Conventional types of waveforms popularly used in high temperature low cycle fatigue testing have been shown in Figure 1. The Metals Properties Council Inc. /2/ used complex cycles in the generation of creep-fatigue data. Combined cycles were used to investigate interspersion effects. Such cycles contain a pre-determined number (n) of pure fatigue cycles at the end of a creep-fatigue test involving a period of hold. Such a combined cycle is shown in Figure 2.

Table 5
Creep-fatigue data of 0.5Cr-Mo-V Batch 1 (Ref. 1).

Total strain range (%)	Hold time (hours)	Test tem-perature (°C)	Observed cycles (Nƒ)	Remarks
1.51	0.5	550	375	
1	0.5	"	537	
0.70	0.5	"	998	
1.02	2	"	519	
1	16	"	340	
0.4	16	"	1590	
2.39	16	"	124	
1.25	16	"	314	
0.61	16	"	604	
0.43	16	"	675	
0.34	16	"	1249	
2.3	16	"	209	
0.92	16	"	611	
0.62	16	"	647	
0.4	16	"	1126	
0.3	16	"	1700	



No.	Strain wave pattern	Strain vs. time diagram	Δε (%)	th (min)
B-1	Fast-fast	$\dot{\varepsilon}$ = 0.5%/s	2.0,1.2,0.8 0.6,0.4	—
B-2	Slow-fast	$\dot{\varepsilon}$ = 0.01 and -0.5%/s	2.0,1.2,0.8 0.6,0.4	—
B-3	Fast-slow	$\dot{\varepsilon}$ = 0.5 and -0.01%/s	2.0,1.2,0.8 0.6,0.4	—
B-4	Slow-slow	$\dot{\varepsilon}$ = 0.01%/s	2.0,1.2,0.8 0.6,0.4	—
B-5	Fast-fast with hold time in tension	$\dot{\varepsilon}$ = 0.5%/s	2.0	5
			1.0	5
			1.0	30
B-6	Fast-fast with hold time in compression	$\dot{\varepsilon}$ - 0.5%/s	2.0	5

Fig. 1: Illustration of waveforms used in the creep-fatigue characterization of 2.25Cr-Mo steel under benchmark project /9/.

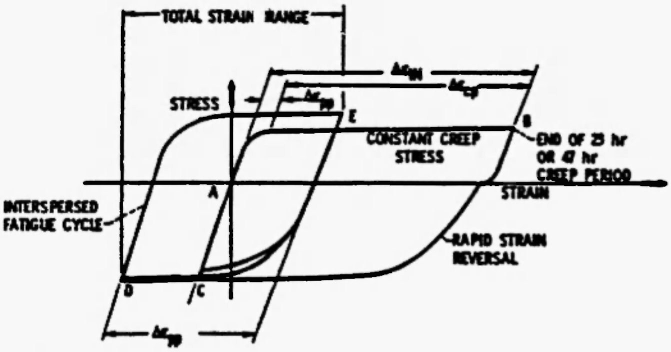


Fig. 2: Schematic hysteresis loops associated with MPC creep-fatigue interspersion tests /2/.

Table 6

Creep-fatigue data of 1Cr-Mo-V Batch 1 (Ref. 2)

Total strain range (%)	Hold time (hours)	Test tem-perature (°C)	Observed cycles (Nf)	Remarks
0.55	23	540	29	n=1
1.50	23	"	22	"
1.10	47	"	24	"
1.50	47	"	29	"
1.50	23	"	42	n=2
0.55	47	"	84	n=1
1.50	47	"	87	"
1.50	23	"	209	"
1.50	47	"	150	"
0.55	47	485	27	n=22
0.55	47	485	48	"
1.50	47	"	30	n=1
1.50	23	"	42	n=2
1.50	23	"	145	"
0.55	23	"	149	"
0.55	23	"	25	n=22
1.50	47	"	87	n=1
0.55	47	"	96	"

Table 7

Creep-fatigue data of 1Cr-Mo-V Batch 2 (Ref. 3)

Total strain range (%)	Hold time (hours)	Test tem-perature (°C)	Observed cycles (Nf)	Remarks
0.55	0	538	5105	
1.5	0	"	520	
0.55	23	538	130	n=22.5
1.5	23	"	68	n=5.5
0.55	0	483	8400	
1.5	0	"	500	
1.5	23	483	49	n-5.5
0.55	47	"	96	n=1.5
0.55	47	"	149	n=2.5
0.55	23	"	161	n=5.5

Table 8
Creep-fatigue data of 1Cr-Mo-V Batch 3 (Ref. 4)

Inelastic strain (%)	Total strain (%)	Test temperature (°C)	Observed cycles (Nf)	Remarks
1.27	1.95	550 (CC)	208	Hold times are unspecified and total strain range is calculated approximately
0.84	1.5	CC types	283	
0.57	1.2		400	
1.6			165	
2.57			165	
2.29			90	
0.946	1.6	t/0 or CP types	340	
1.004	1.67		240	
1.038	1.72		180	
2.257			52	
0.95	1.62		171	
0.708	1.35		340	
1.554			113	
2.33		0/t or PC types	92	
1.297	1.98		285	
1.14	1.81		250	
2.18			95	
0.24	0.83		1460	
0.24	0.83		1230	
0.76	1.41		380	
1.32	2		185	
1.11	1.78		255	
0.5	1.13		590	
0.3	0.9	t/t or CC types	625	
0.57	1.2		350	
1.167	1.84		180	
1.923			108	
0.892	1.55		260	
0.369	0.98		600	
0.093	0.6		950	

Table 9
Creep-fatigue data of 1Cr-Mo-V Batch 4 (Ref. 5-6).

Total strain range (%)	Hold time (hours)	Test temperature (°C)	Observed cycles (Nf)	Remarks
1.5	0	565	327	Stress range is unknown, inelastic strain range unknown.
1.0	0	"	490	
0.7	0	"	960	
1.96	3	"	97	
1.08	3	"	150	
1.96	0.5	"	135	
1.08	0.5	"	220	
0.53	0.5	"	435	
0.86	1	"	1275	
1.06	0.5/.0.5	"	385	
1.46	0.5/0.5	"	220	
2.0	0.5/0.5	"	215	
1.4	0.5/0.5	"	390	
1.3	16	"	73	
1.3	16/0.003	"	208	
2.0	0.5	"	180	
1.5	0.5	"	215	
1.0	0.5	"	300	
2.0	0/0.5	"	300	
1.5	0/0.5	"	374	
1.1	0/0.5	"	560	
2.04	0/0.5	"	320	
1.24	0/0.5	"	562	
1.53	0/0.5	"	362	
0.85	0/0.5	"	500	

Table 10
Creep-fatigue data of 1Cr-Mo-V Batch 5 (Ref. 1).

Total strain range (%)	Hold time (hours)	Test temperature (°C)	Observed cycles (Nf)	Remarks
3.2	0.5	550	80	
2	0.5	"	176	
1	0.5	"	382	min. value
0.9	0.5	"	500	
0.6	0.5	"	1456	
0.5	0.5	"	2300	
1	2	"	448	
3.19	16	"	86	
1.23	16	"	244	
0.84	16	"	454	
0.63	16	"	1033	
0.5	16	"	3557	
3.74	16	"	122	
1.16	16	"	645	
0.61	16	"	2347	
0.48	16	"	4084	

Table 11
Creep-fatigue data of 1.25Cr-Mo Batch 1 (Ref. 7).

Total strain range (%)	Hold time (hours)	Test temperature (°C)	Observed cycles (Nf)	Test end criterion
0.5	0	550	5284	20% load drop
0.7	0	"	1667	"
1.0	0	"	945	"
0.5	0.0166	"	3919	"
0.7	0.0166	"	1475	"
1.0	0.0166	"	769	"
0.5	0.166	"	3896	40%
0.7	0.166	"	1311	33%
1.0	0.166	"	820	20%
1.0	0.5	"	601	20%

Table 12
Creep-fatigue data of 1.25 Cr-Mo Batch 2 (Ref. 8).

Total strain range (%)	Hold time (hours)	Test temperature (°C)	Observed cycles (Nf)	Saturated stress range (Nf/2) MPa
2.01	0	600	560	575
1.52	0	"	760	527
0.98	0	"	1500	505
0.62	0	"	6100	460
0.59	0	"	5800	459
0.48	0	"	5000	438
2.04	0.03	"	418	599
1.04	"	"	871	526
2.05	0.08	"	327	583
0.95	"	"	772	533
2.04	0.16	"	292	583
1.04	"	"	605	522
2.03	0.5	"	230	551
1.04	"	"	455	488
2.03	1	"	195	528
0.99	"	"	418	481

Table 13
Creep-fatigue data of 2.25Cr-Mo Batch 1 (Ref. 2).

Total strain range (%)	Hold time (hours)	Test temperature (°C)	Observed cycles (Nf)	Remarks
0.55	47	540	67	n=1 (annealed)
1.50	23	"	141	"
2.30	47	"	59	"
2.30	23	"	73	"
1.50	23	"	202	"
1.50	23	"	50	n=1 N&T
0.55	47	"	13	"
2.3	47	"	24	"
2.3	23	"	43	"
0.55	47	"	60	"
1.5	23	"	110	"
0.55	47	485	23	n=1 Q&T
1.50	23	"	31	"
2.3	47	"	15	"
2.3	23	"	29	"
0.55	47	"	48	"
1.50	23	"	77	"

Table 14
Creep-fatigue data of 2.25Cr-Mo Batch 2 (Ref. 3).

Total strain range (%)	Hold time (hours)	Test temperature (°C)	Observed cycles (N_f)	Remarks
0.55	0	538	3655	Annealed
1.5	0	"	930	"
2.3	0	"	348	"
0.55	47	"	67	n=1.5
0.55	23	"	103	n=5.5
1.50	23	"	13	n=5.5
0.55	0	538	2990	N&T
1.5	0	"	672	"
2.3	0	"	281	"
0.55	47	"	13	n=1.5
0.55	23	"	32	n-5.5
0.55	47	"	60	n=1.5
1.5	23	"	13	n=22.5
0.55	0	483	7440	Q&T
1.50	0	"	474	"
2.3	0	"	265	"
0.55	47	"	23	n=1.5
0.55	23	"	90	n=5.5
1.50	23	"	77	n=1.5

Table 15
Creep-fatigue data of 2.25Cr-Mo Batch 3 (Ref. 9).

Total strain range (%)	Hold time (hours)	Test temperature (°C)	Observed cycles (N_f)	Remarks
2.0	-	600	257	Five strain rates
"	-	"	355	fast-fast (FF)
1.2	-	"	780	0.5%/s
"	-	"	668	slow-fast
0.8	-	"	2008	0.01 and -0.5%/s
"	-	"	1294	fast-slow
0.6	-	"	3865	0.5 & -0.01%/s
"	-	"	2100	slow-slow
0.4	-	"	7786	0.01%/s
"	-	"	6742	FF with tensile
"	-	"	6075	hold=0.5%/s
2.1	-	"	112	FF with compressive
1.3	-	"	308	hold=0.5%/s
1.2	-	"	350	
0.87	-	"	731	
0.8	-	"	1048	
0.68	-	"	1140	
0.6	-	"	2129	
0.4	-	"	7346	
2.0	-	"	305	
1.2	-	"	540	
"	-	"	678	
0.8	-	"	1049	
"	-	"	1138	
0.62	-	"	2095	
0.6	-	"	2560	
0.4	-	"	5630	
2.0	-	"	224	
"	-	"	168	
1.2	-	"	325	
"	-	"	496	
0.86	-	"	915	
0.8	-	"	955	
0.6	-	"	1768	
"	-	"	1229	
0.4	-	"	9227	
2.0	0.083	"	312	
1.0	0.083	"	720	
2.0	0/0.083	"	325	
1.0	0/0.083	"	894	

Table 16

Creep-fatigue data of 2.25Cr-Mo Batch 4 (Ref. 10)

Total strain range (%)	Hold time (hours)	Test temper-ature (°C)	Observed cycles (N*f*)	Saturated stress range (N*f*/2) MPa
0.5	0/0.1	502	61111	216
0.5	0.1	"	20147	209
0.5	0.1/0.1	"	3420	209
1.0	-	"	3721	259
1.0	0/0.1	"	1924	264
1.0	0.1	"	2059	252

Table 17

Creep-fatigue data of 2.25Cr-Mo Batch 5 (Ref. 11)

Total strain range (%)	Hold time (hours)	Test temper-ature (°C)	Observed cycles (N*f*)	Inelastic strain range (%)
1.01	0.23	600	1360	0.79
1.99	0.22	"	472	1.75
1.00	0.01	"	1070	0.79
1.07	0.54	"	820	0.9
1.02	0.08	"	940	0.85
1.97	0.22	"	410	1.78

Table 18

Creep-fatigue data of 2.25Cr-Mo Batch 6 (Ref. 12)

Total strain range (%)	Hold time (hours)	Test temper-ature (°C)	Observed cycles (N*f*)	Saturated stress range (N*f*/2) MPa
3.20	0.016	550	234	697
2.15	"	"	410	647
0.54	"	"	5200	485
1.05	"	"	1520	549
4.30	"	"	200	722
3.20	"	"	208	687
2.20	"	"	380	630
1.20	"	"	150	736
0.52	"	"	6100	422
1.05	"	"	1450	510
4.25	0.034	"	165	657
3.00	"	"	280	608
2.10	"	"	440	574
1.15	"	"	1200	490
0.68	"	"	2200	432
4.1	0.166	"	180	549
3.0	"	"	265	520
2.2	"	"	345	515
1.2	"	"	1070	427
0.66	"	"	2300	353
4.0	"	"	220	530
3.1	"	"	255	535
2.1	"	"	410	471
1.1	"	"	1180	408
0.60	"	"	2750	334

Table 19

Creep-fatigue data of 2.25Cr-Mo Batch 7 & 8 (Ref. 13).

Total strain range (%)	Hold time (hours)	Test temper-ature (°C)	Observed cycles (N*f*)	Saturated stress range (N*f*/2) MPa
0.523	-	593	7179	478
0.544	-	"	5100	436
0.773	-	"	2980	478
0.84	-	"	799	492
0.86	-	"	1065	402
0.92	-	"	2647	498
0.927	-	"	2699	520
0.973	-	"	1623	450
0.993	-	"	2443	450
1.41	-	"	1109	492
1.84	-	"	777	510
2.33	-	"	555	582
0.557	**Batch 8**	"	5072	535
0.571	-	"	4645	591
0.813	-	"	2734	634
0.933	-	"	505	622
0.94	-	"	1201	536
0.984	-	"	301	680
1.024	-	"	1904	613
1.027	v = 1.027% /s	"	2159	632
1.040	=0.042%/s	"	1519	470
1.40		"	861	620
1.90		"	605	685

Table 20

Creep-fatigue data of 9Cr-1 Mo Batch 1 (Ref. 14).

Total strain range (%)	Hold time (hours)	Test tem-perature (°C)	Observed cycles (N_f)	Remarks
2.0	-	550	780	Other details are not known
"	-	"	935	
"	-	"	947	
1.2	-	"	1839	
"	-	"	1852	
"	-	"	1740	
0.6	-	"	16960	
"	-	"	13000	
"	-	"	10300	

Table 21

Creep-fatigue data of 9Cr-1Mo Batch 2 (Ref. 15).

Total strain range (%)	Hold time (hours)	Test temper-ature (°C)	Observed cycles (N_f)	Saturated stress range ($N_f/2$) MPa
0.5	0/0	538	13786	535
0.5	0/0	"	15455	604
0.7	0/0	"	6844	556
0.7	0/0	"	9676	549
0.78	0.25	"	3537	482
0.5	0.25	"	8840	475
0.5	0.5	"	6975	508
0.51	0.5	"	7770	513
0.52	0/0	593	13125	505
0.49	0/0	"	7420	472
0.5	0.5	"	3360	426
0.5	0.5	"	4150	465
0.5	1	"	3207	370
0.5	1	"	2870	203
0.5	1	"	2882	363
0.5	1	"	2900	429

Comments on the Data Compiled

In all cases certain test and material features were unspecified. Effects of microstructure on creep-fatigue life were ignored by most authors. Strain rates during the creep-fatigue tests were also unspecified in the published literature. Total strain range and hold times were unspecified in the data /4/ (Table 8). This was calculated approximately by using the following equations:

$$\Delta\varepsilon_t = \Delta\sigma / E + \Delta\varepsilon_p$$
$$\Delta\sigma = K(\Delta\varepsilon_p)^n \qquad (1)$$

where $\Delta\varepsilon_t$, total strain range, $\Delta\sigma$, stress range, E, modulus of elasticity, $\Delta\varepsilon_p$, plastic strain range, K, fatigue strength constant, and n is the slope. Values of K and n were approximated from Jaske and Mindlin /17/, as 1008 and 0.09, respectively. They characterized 1Cr-Mo-V at 538°C. Such conversions from inelastic strain to total strain were made below the inelastic strain range of 1.4%. Beyond this limit, the two assumed values changed.

The saturated stress ranges at half life were also scarce in the literature. Hence, they appear in the data tables where available. In most cases, longitudinal specimens were used; however, complete details of the specimen, extensometry and the ways of controlling temperature and strain rates were not specified. A code of practice /18/ has recently been developed in the U.K.; however, several test parameters have not been standardized. Hence, for the laboratory creep-fatigue test, a standard of practice is required to generate such data. It is felt that the research community would benefit if all details were made available with the data.

PART II:
TRENDS IN THE CREEP-FATIGUE BEHAVIOR

The sources of variability in creep-fatigue data have been identified in the preceding Part I. There are considerable variations between the normalizing and tempering temperatures, periods of soaking and cooling rates. These differences were observed for the same grade of steel within the same N&T condition. Cooling types such as furnace, water and air are used for the same heat treatment cycle for different batches. Thus the contribution of such variations on the creep-fatigue performance becomes an independent area to explore; besides, such effects have been isolated to identify trends in the creep-fatigue performance.

Data Analysis

The data compiled in Part I dealt with total strain and life; total strain range versus life data are analyzed on a log-log plot. A least square fit equation was determined for a particular condition. There were 50 such combinations of continuous fatigue and hold time waveform combinations. The best fit equation so obtained has an intercept (A) and a slope (m). In many instances, for want of adequate data points, only two data points were used to determine the parameters of linear extrapolation. Such extrapolations are quite questionable and should not be used in the design. With decreasing creep-fatigue life, the negative slope (m) and intercept (A) increased. Since the life range of the data compiled were from two to four digits, plastic strain dominates in the low cycle regime and the elastic component is expected to be smaller than the plastic strain. Hence, total strain versus life extrapolations have been conducted in the following form of equation (2):

$$\Delta\varepsilon_t = A\,(N_f)^m. \qquad (2)$$

where A and m are material parameters, values of which were tabulated in Table 22 for as many as 50 combinations.

Where material parameters have been determined from two data points, they are denoted by (*). The symbol (#) is used with inelastic strain range versus life relations. Tabulation of material parameters of equation (2) makes construction of those figures irrelevant.

Creep-Fatigue Behavior of Low Alloy Steels – Trends

Trends in the creep-fatigue behavior of low alloys steels are identified in Part II of this paper from the data compiled in Part I. Trends in the following were investigated:

1. Effects of waveform,
2. Effects of product form,
3. Effects of compositional variations.

Table 22

Material parameters of total strain versus life equations of the compiled data.

Material / (Batch)	Temperature	Slope	Intercept	Remarks
0.5Cr-Mo-V (1)	550°C	-0.77	2.12	0.5 hour tensile hold.
	550°C	-0.84	2.18	16 hours tensile hold.
1Cr-Mo-V (1)	540°C	-3.63*	4.30	23 hour hold. (n=1)
	485°C	-0.80*	1.46	23 hour hold. (n=2)
	485°C	-10.2*	19.9	47 hour hold. (n-1)
Batch 2	538°C	-0.44*	1.36	0/0 continuous fatigue.
	483°C	-0.36*	1.36	0/0 continuous fatigue.
	483°C	-0.84*	1.6	23 hour hold. (n=5.5)
Batch 3	550°C	-1.03	2.47	CC type of SRP loop$^{\#}$.
	550°C	-0.54	1.27	CP type of SRP loop$^{\#}$.
	550°C	-0.17*	0.40	PC type of SRP loop$^{\#}$.
	550°C	-1.04	2.45	CC type of SRP loop$^{\#}$.
Batch 4	565°C	-1.36*	3.0	3 hours hold data.
	565°C	-1.22*	2.89	1/2 hour hold data.
	565°C	-0.85	2.22	Balanced dwell of 1/2 hr.
	565°C	-1.34	3.31	1/2 hr. hold.
	565°c	-1.04	2.87	0/0.5 hr.hold.
Batch 5	550°C	-0.56	1.52	0.5 hour tensile hold.
	550°C	-0.51	1.4304	16 hours tensile hold.
1.25Cr-Mo (1)	550°C	-0.39	.96	0/0 continuous fatigue.
	550°C	-0.42	1.19	0.016 hr. hold.
	550°C	-0.42	1.19	0.16 hr. hold
Batch 2	600°C	-0.52	1.67	0/0 continuous fatigue.
	600°C	-0.92*	2.71	0.03 hr. hold.
	600°C	-0.89*	2.5	0.08 hr. hold.
	600°C	-0.92*	2.58	0.16 hr. hold
	600°C	-0.98*	2.6	1/2 hr. hold.
	600°C	-0.94*	2.46	1 hr. hold.
2.25Cr-Mo (1)	540°C	-11.25*	20.3	47hr. hold, Annealed(A)
	540°C	-0.419*	1.14	23 hr. hold, A.
	540°C	-2.83*	4.99	23 hr. hold, N&T.
	540°C	-1.56*	2.5	47 hr. hold, N&T.
	485°C	-6.4*	9.73	23 hr. hold, Q&T.
	485°C	-3.34*	4.29	47 hr. hold, Q&T.
Batch 2	538°C	-0.61	1.94	0/0 continuous fatigue A.
	538°C	-0.61	1.87	0/0, N&T.
	483°V	-0.40	1.32	0/0, Q&T.
Batch 3	600°C	-0.44	1.25	0/0 N&T.
	600°C	-0.83*	2.3	0.08 hr.tensile hold N&T

Table 22 continued

	600°C	-0.68*	2.0	0.08 hr. compression.
Batch 4				Not enough data.
Batch 5				Not enough data.
Batch 6	550°C	-0.46	1.51	0.016 hr. hold.
	550°C	-0.69	2.17	0.034 hr. hold.
	550°C	-0.7	2.18	0.166 hr. hold.
Batch 7	593°C	-0.46	1.48	0/0 continuous fatigue.
Batch 8	593°C	-0.274	0.83	0/0 continuous fatigue.
9Cr-1Mo (1)	550°C	-0.42	1.5	0/0 continuous fatigue
Batch 2	538°C	-0.49	1.72	0/0 continuous fatigue
	538°C	-0.49*	1.62	1/4 hr. tensile hold.
	538°C	0.18*	-1.01	1/2 hr. tensile hold, within $\Delta\varepsilon_t$=0.5-0.51%
	593	0.11	-0.72	0/0 continuous fatigue within $\Delta\varepsilon_t$=0.52-0.49%

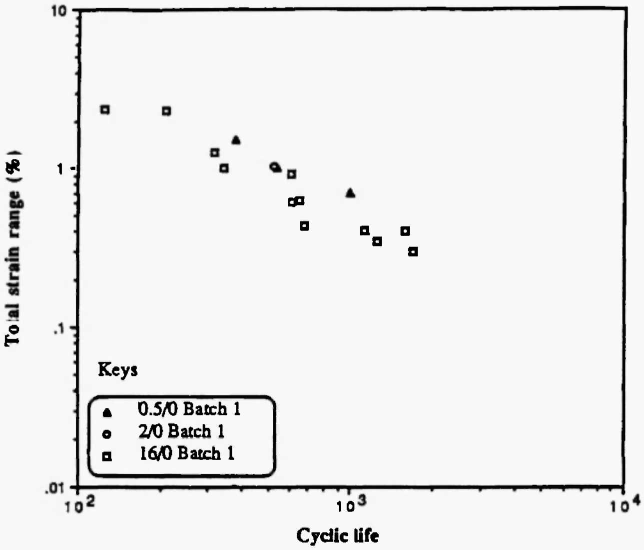


Fig. 3: Creep-fatigue behavior of 0.5Cr-Mo steel with different hold times.

Effects of Waveform:

0.5Cr-Mo-V Steel: creep-fatigue data of 0.5Cr-Mo-V steel are plotted in Fig. 3. The hold times applied were 30 min. and 16 hours in the peak tensile strain direction. No compressive dwell data are available to compare the tensile and compressive behaviors. The slopes of the total strain versus life for the two hold time cycles do not show appreciable differences. Such long hold times caused considerable reduction in life in the case of 1Cr-Mo-V steel. The life debit from a hold cycle with respect to a continuous fatigue or (0/0 no hold) cycle depends upon the strain range. At lower strain ranges, the life debit was found to be higher, which with the increase in the total strain range saturates. This phenomenon has been observed when the total strain range versus life of a hold containing cycle, normalized by cycles to failure under continuous fatigue, is plotted in the case of 1Cr-Mo-V, 2.25Cr-Mo and 9Cr-1Mo steels.

1Cr-Mo-V Steel: This particular low alloy steel grade was found to be tensile dwell sensitive. For such materials tensile dwell causes more damage and reduces the cyclic life at the same strain range and temperature more than the dwell in the compression direction, equal dwells in both directions (balanced dwell cycles), and unequal dwells. Table 9 tabulates the effect of hold times in either direction for "Batch 4". Although the same hold periods were applied at the same strain, tensile holds were nearly twice as damaging. Material parameters, such as the slope of 30 min. tensile dwell cycles, were more negative as compared to the same compressive dwells. These values are tabulated in Table 22. Tensile dwell of 30 min. duration had a slope of -1.22, whereas for the same compressive hold, the slope was -1.04. Unbalanced cycles with 16 hours tensile hold, followed by a small fraction (1/8000 of tensile hold) in compression, caused a healing effect. The life was enhanced by a factor of 3 from tensile hold of only 16 hours. Data contained in five batches, in Tables 6-10, of 1Cr-Mo-V are shown in Fig. 4.

In the case of creep-fatigue interactions where a dwell effect accumulates, creep damage follows through stress or strain relaxations, which occur under constant strain or stress holds respectively. When the magnitude of the relaxed strains exceeds the creep ductility, failure occurs /19/. Creep-ductility of Batch 4, characterized in a forged form, was determined as approximately 5% /20/, depending upon stress, temperature, and time. Apart from the above factors, creep-ductility also depends on material heat and compositions. Exhaustion of ductility or strain accumulation per cycle for tensile

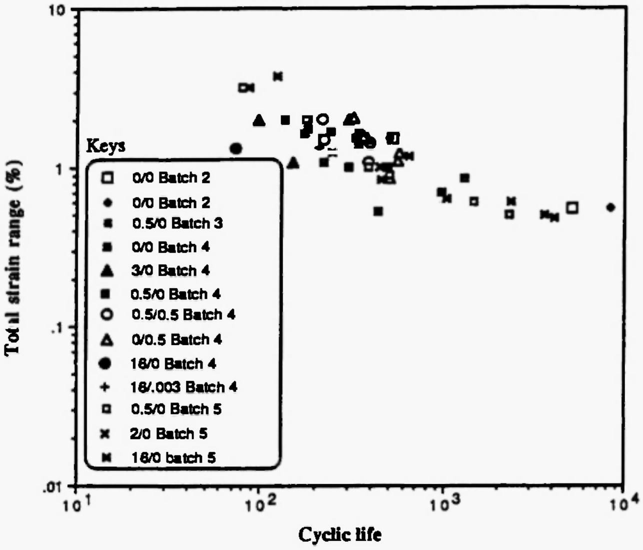


Fig. 4: Creep-fatigue behavior of 1Cr-Mo-V steel with different hold times.

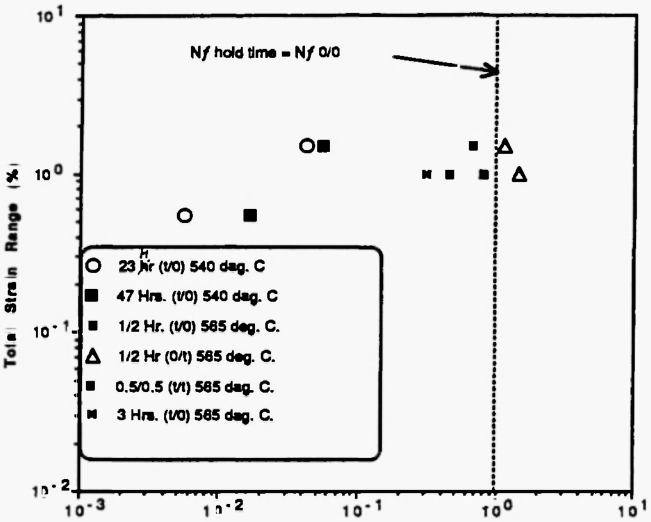


Fig. 5: Normalized life ratio of various dwell cycles of 1Cr-Mo-V steel.

dwell was higher than in the cycles with no hold. It is assumed that the rates of stress relaxation occurring under hold times are the same in both the tension and compression directions. However, in theory, this is not the case from a mechanistic point of view. Knowledge of this particular behavior in the tension and compressions directions needs to be gained, to predict the creep-fatigue behavior and life of high temperature materials.

Various dwell containing data are normalized by continuous fatigue data in terms of a normalized cycle ratio, and are plotted with respect to total strain range in Fig. 5. When the normalized cycle ratio of various tensile dwell containing cycles is less than unity, the material is tensile dwell sensitive. However, when the normalized cycle ratios of the compressive dwell containing cycles exceed one, they are beneficial, since the life of compressive hold containing cycles is higher than the continuous fatigue response.

1.25Cr-Mo Steel: Material conditions and heat treatment details were unknown for Batch 1 (Table 11). Since these were unknown, compiled data of two batches of 1.25 Cr-Mo steels were compared isolating the material conditions. Test temperatures were different for the two batches of 1.25Cr-Mo steel compiled in Tables 11 and 12. A test temperature difference of 50°C, within the temperature range of 500-600°C, contributes more to the damage and deteriorates tensile and creep-fatigue properties of the low-alloy steels. Owing to the lack of more identical data, the effect of such a temperature variation was ignored when investigating the trends in the creep-fatigue behavior. In the same total strain ranges, both materials performed identically under 0/0 conditions. With 10 and 30 minutes tensile hold in the same strain range, the creep-fatigue response of Batch 1 was slightly better than that of Batch 2, as shown in Fig. 6. It may not be possible to conclude whether a decrease in temperature from 600 to 550°C increased life by a factor of 1.25, or, isolating temperature effects, material in as-received condition performed better.

Various dwell containing data are normalized by continuous fatigue data in the same strain range and plotted with respect to total strain range in Fig. 7. As the normalized cycle ratio of various tensile dwell containing data is much less than unity, the material is tensile dwell sensitive.

2.25Cr-1Mo Steel: This was a compressive dwell sensitive material, where damage of a compressive dwell in the same strain range and the same temperature was greater than that of dwell in the tension direction /21/. Challenger *et al.* /10/ explained that possibly such a behavior was due mainly to

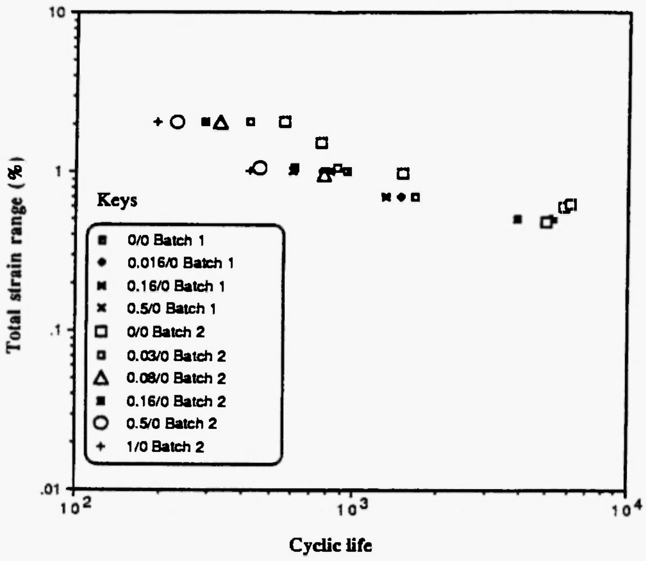


Fig. 6: Creep-fatigue behavior of 1.25Cr-Mo steel with different hold times.

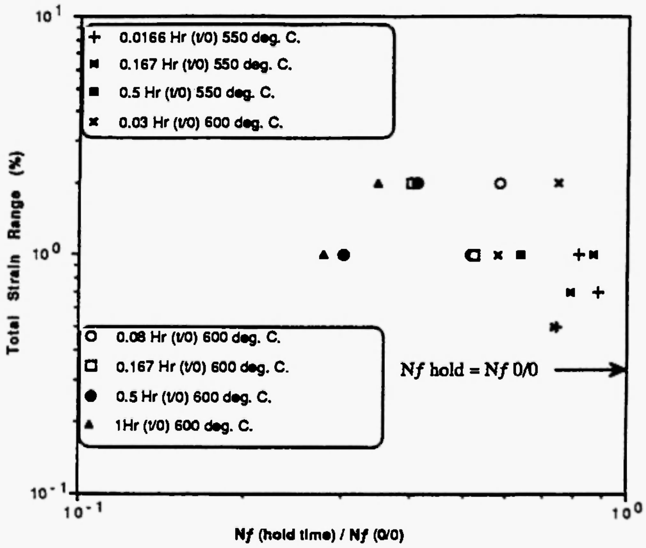


Fig. 7: Normalized life ratio of various dwell cycles of 1.25Cr-Mo steel.

oxidation. The oxide cracking that occurs in the case of 2.25Cr-1Mo steels was found /10/ to be a function of strain range, temperature and time of hold in the peak compressive loading direction. Later the evidence of oxidation of this alloy was reported by Teranishi and McEvily /13/ at 593°C, and Narumoto /22/. A threshold in the temperature range was observed /21,22/, above which oxidation damage occurs. This temperature was found to be 450°C /21/ and was lower (250 - 350°C) for the steel studied by Narumoto /22/.

Apart from the temperature thresholds, there was also a time of hold criterion, below which life debit does not occur. Five-minute tensile and compressive dwell cycles were assessed in Fig. 8, under N&T condition, tested at 600°C for Batch 3. Creep-fatigue lives under such hold periods were between the maximum and mean response of continuous fatigue behavior.

In summary, the following waveform effects were observed by Brinkman:

1. compressive hold times were more damaging than the tensile holds in low strain ranges, where resistance to crack nucleation governs the lifetime /21/,
2. a balanced cycle in the low strain range was found to be more damaging than the cycle having only one tension or compression dwell of the same time /21/, and
3. compressive hold periods were more deleterious because they developed a positive mean stress at low strain ranges and shifted the hysteresis loop in the tensile direction.

Apart from that there were interactions of creep and fatigue with oxidation.

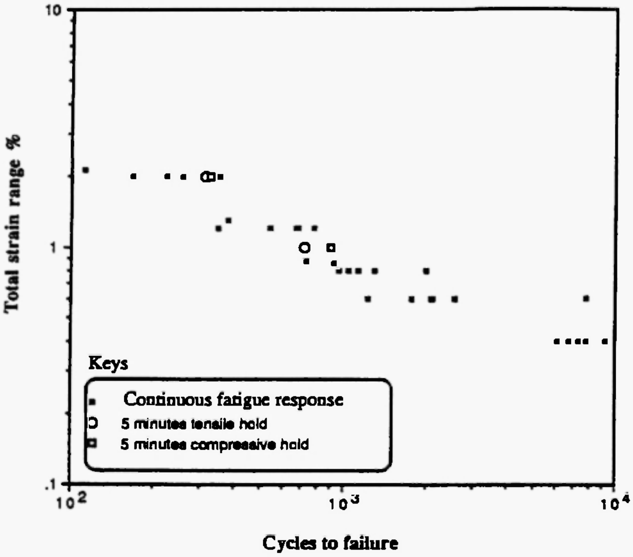


Fig. 8: Scatter plot with 5 minutes and without hold of 2.25Cr-Mo steel (batch 3).

Various dwell containing data were normalized by continuous fatigue data and plotted with respect to total strain range in Fig. 9. As the normalized life ratio of various tensile dwell containing cycles was close to unity or higher, the material was compressive dwell sensitive. However, the normalized cycle ratio of the compressive dwell containing cycles was less than unity and was detrimental as the life of compressive hold containing cycles was smaller than its continuous fatigue response.

9Cr-1Mo Steel: The creep fatigue data compiled in Part I comprised only two batches. There were several hold times and 0/0 combinations with only two data points and the extrapolated relations were quite questionable. As for the behavior of 9Cr-1Mo steel, when compared with other low alloy steels, the trends were similar in terms of creep-fatigue performance. These data were plotted in Fig. 10.

Various dwell containing data were normalized by continuous fatigue data and plotted with respect to total strain range in Fig. 11. As the normalized life ratio of various tensile dwell containing cycles was much below unity, the material was tensile dwell sensitive. However, compressive dwell data were not available to make a comparison with tensile dwells.

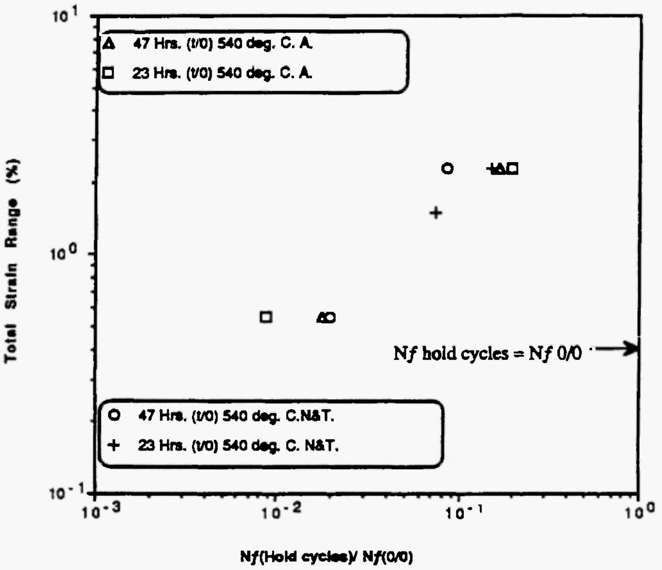


Fig. 9: Normalized life ratio of various dwell cycles of 2.25Cr-Mo steel.

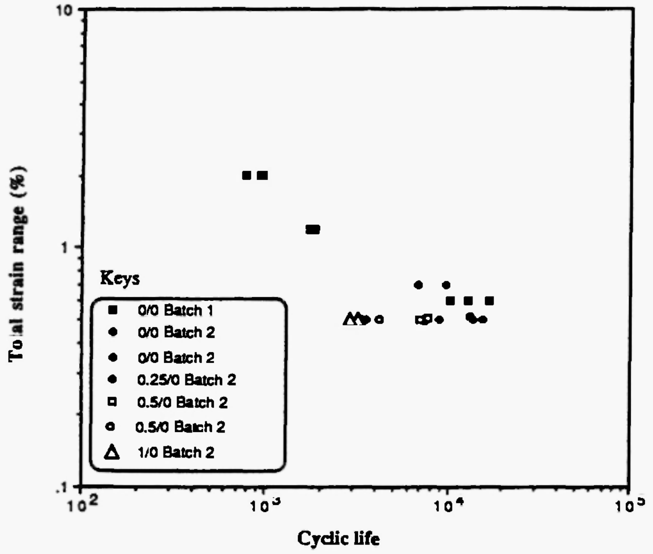


Fig. 10: Creep-fatigue behavior of 9Cr-1Mo steel with different hold times.

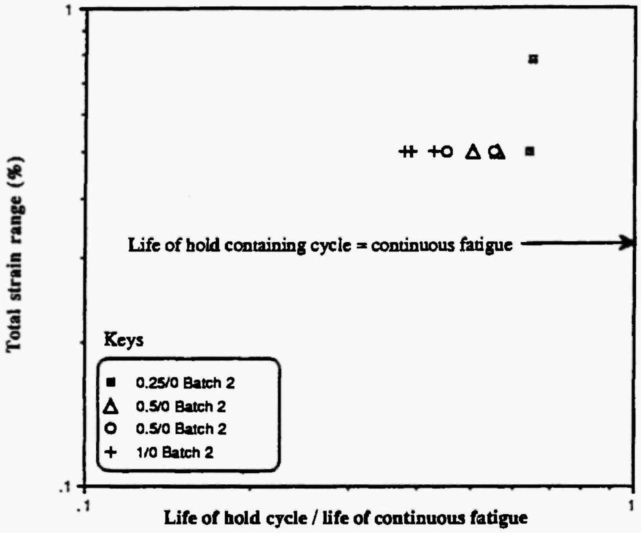


Fig. 11: Normalized life ratio of various dwell cycles of 1Cr-Mo-V steel.

Effect of Combined Cycles on the Performance of 1Cr-Mo-V

A combined cycle comprised, in addition to a tensile dwell, a specified number of pure fatigue cycles, as shown in Fig. 2. Combined cycles were applied after a tensile dwell of 23 and 47 hours. Table 23 tabulates the effect of combined cycles on the creep-fatigue performance of Batches 1 and 2. Continuous fatigue

Table 23
Effect of combined cycles on the performance of 1Cr-Mo-V steel

Strain range (%)	Hold time t_h (hr)	Temperature (°C)	*Nf*	n	Increase from t_h 47 hr. & n=1(times)	Decrease from 0/0 data (times)
0.55	0	483	8400	0	-	-
0.55	47	485	27	1		311
0.55	47	483	96	1.5	3.55	87.5
0.55	47	485	149	2	5.51	56.37
0.55	47	483	149	2.5	5.37	58
0.55	47	485	48	22	1.7	175

Table 24
Effect of combined cycles on the performance of 1Cr-Mo-V steel

Strain range (%)	Hold time t_h (hr)	Temperature (°C)	*Nf*	n	Increase from t_h 23 hr. & n=1(times)	Decrease from 0/0 data (times)
0.55	0	538	5105	0	-	-
0.55	23	540	29	1		170
0.55	23	538	157	5	5.4	32.5
0.55	23	540	130	22	4.48	39.26

Table 25
Effect of combined cycles on the performance of 1Cr-Mo-V steel

Strain range (%)	Hold time t_h (hr)	Temperature (°C)	*Nf*	n	Increase from t_h 23 hr. & n=1(times)	Decrease from 0/0 data (times)
1.5	0	538	520	0	-	-
1.5	23	540	22	1		23.63
1.5	23	538	68	5.5	3.09	7.64
1.5	23	540	11	22	0.5	47.27

behavior was recorded and compared with 23 and 47 hours tensile hold data with one fatigue cycle (n=1). A 47 hours hold, at 485°C, with (n=1), reduces the life 311 times from its 0/0 data, in 0.55% total strain range. In the same strain range, 540°C, this factor was 170 times, Table 24. However, with increasing strain range (1.5%) and temperature (540°C), and 23 hour hold time with n=1, life was reduced by 24-fold from its 0/0 performance, Table 25. When the number of fatigue cycles increased from 1 to 22, the creep-fatigue performance decreased with respect to n=1 data. A maximum beneficial effect was observed when the number of pure fatigue cycles ranged from 1 to 5.5. Beyond this, in the case of n=22, a decreasing trend of cyclic life, compared with n=1, was observed. The effect of combined cycles was tabulated in Tables 23-25.

The mechanisms of the combined cycles in the creep-fatigue behavior are unknown. Combined cycles that either enhanced the creep-fatigue performance with n=2.5 to 5 or deteriorated it with n=22, for want of a possible reason, were surmised to have been caused for the following reason(s):

1. More strain accumulation per cycle, causing ductility exhaustion,
2. Strain rate resulting from 23 and 47 hour hold times are likely to be much lower than the critical strain rate that causes cavitation and the material cavitates, and
3. More interaction between creep-fatigue and oxidation.

However, the mechanisms associated with the application of up to 5 fatigue cycles and beyond were unknown.

Effect of Combined Cycles on the Performance of 2.25Cr-Mo

Trends quite similar to those observed for 1Cr-Mo-V steel were also found in the case of 2.25Cr-Mo steel. Very limited data on 2.25Cr-1Mo in an annealed condition were analyzed collectively from Batches 1 and 2 and are presented in Table 26.

The only beneficial effect observed was that for n=5.5, where life increased 1.2 times compared with n=5. In general, it was seen that the combined cycles were not as advantageous for this alloy as in the case of 1Cr-Mo-V steel. Complex damage interactions of oxidation with creep-fatigue were expected. The oxidation damage expected was based upon the evidence of a threshold temperature limit of 250-450°C /21,22/.

Effect of Product Form

On Performance of 1Cr-Mo-V: Details regarding the product form, production and manufacturing histories were not included by all laboratories in characterizing a material for creep-fatigue. Hence, those details were not compiled in Part I of this paper. A comparative plot of low cycle fatigue performance of three batches, 2, 3 and 4 respectively, of 1Cr-Mo-V steel is shown in Fig. 4. Batch 3, characterized in the hot rolled bar form, had a higher life compared to the forged condition of Batch 4. The 0/0 behavior, in the same total strain range, of Batch 2, was superior to that of Batch 4. Batch 2's behavior was nearly twice as high as Batch 4, when there was a temperature difference of 25°C. Batch 4, in the same total strain range and for tensile dwells, exhibited life inferior to Batch 3. The test temperature for hot rolled bar, Batch 3, was 15°C lower than for Batch 4. Complete details of Batch 3 were not published and several assumptions were made to determine various test parameters in Part I. Only a few data points with CP sequence of Batch 3 that involved tensile holds of 30 min. /23/ were compared with Batch 4, where Batch 4 was found inferior to Batch 3. For a 30 minutes tensile dwell in a 2% total strain range, life was at least one and a half times higher in the case of Batch 3 at 550°C than for Batch 4 at 565°C. It may not be possible to pinpoint whether a temperature increase of 15°C reduced the creep-fatigue life of Batch 4, or the material condition of Batch 3 enhanced creep-fatigue performance. A conclusion may be drawn from Fig. 4 that, although there were differences in the testing parameters and material conditions, Batch 3 exhibited higher lives in a ferritic form in the same strain range and tensile dwells, compared with the tempered bainitic form of Batch 4.

Table 26

Effect of combined cycles on the performance of 2.25Cr-Mo steel

Strain range (%)	Hold time t_h (hr)	Temperature (°C)	N*f*	n	Increase from t_h 23 hr. & n=1(times)	Decrease from 0/0 data (times)
1.5	0	538	930	0	-	-
1.5	23	540	141	1		6.5
1.5	23	540	75	5		12.4
1.5	23	538	92	5.5	1.2	10.1
1.5	23	540	29	22		31.72

On Performance of 2.25Cr-Mo Steel: Batches 1 and 2 were characterized following the Metal Properties Council's program on creep-fatigue interactions. Material conditions, heat treatments and compositions were identical along with the test parameters. for the same total strain range and temperature, material in the annealed condition exhibited higher lives than the N&T condition. In a lower strain range (0.55%), Q&T at 485°C was found superior to N&T and the annealed condition tested at a much higher temperature of 540°C. A crossover in the behavior was observed for a strain range of nearly 1% for both N&T and the annealed condition, below which Q&T was found superior in Fig. 12. However, a temperature difference of 55°C was quite considerable and no conclusion should be drawn from such trends.

Compositional Effects:

Compositional effect on performance of low alloy steels: Low alloy steels were classified with respect to

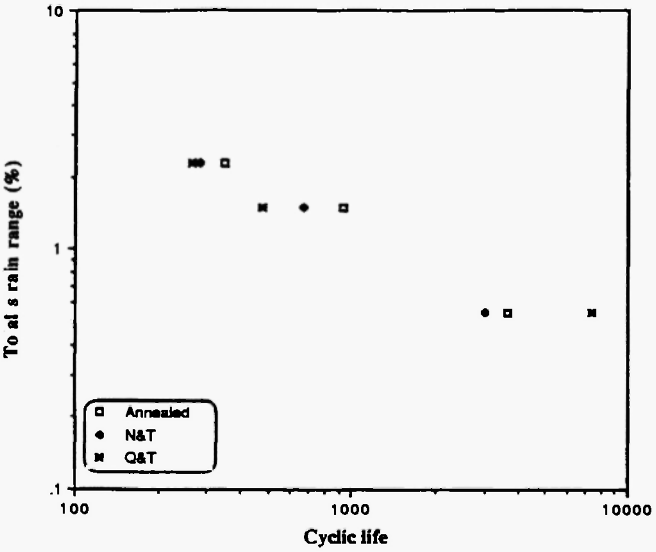


Fig. 12: Effect of heat treatment on the creep-fatigue performance of 2.25Cr-Mo steel.

their per cent chromium content. The following alloy groups were formed, namely, 0.5Cr-Mo-V, 1Cr-Mo-V, 1.25Cr-Mo, 2.25Cr-Mo, 2.25Cr-Mo-V and 9Cr-1Mo steels. The creep-fatigue behavior of these alloys with respect to their chromium content, with or without hold periods, was plotted in Fig. 13. The HTLCF behavior of low alloy steels improved with increasing chromium content. Despite a very limited number of data points, these were analyzed in Fig. 13; there was a large scatter in the HTLCF properties and a general behavior of the material grades may be concluded. Isolating the temperature differences, material conditions, strain rates and microstructures, properties of 1Cr-Mo-V were at the lower extreme. Better properties were observed with the increase in per cent chromium to 1.25Cr-Mo, 2.25Cr-Mo and 9Cr-1Mo. The 9Cr-1Mo steel was observed better than all other conditions at 550°C, where it was at the higher extreme, see Fig. 13.

Effect of vanadium on the HTLCF of 2.25Cr-Mo steel: Batches 7 and 8 were analyzed to investigate the effect of vanadium on the HTLCF properties of 2.25Cr-Mo steel, Fig. 14. With the inclusion of vanadium in a standard alloy 2.25Cr-Mo system, the HTLCF life deteriorated. Despite a large scatter in the data in the higher strain ranges for the 2.25Cr-Mo-V alloy relative to 2.25Cr-Mo steel, supporting data to conclude such a behavior were limited. Compared with Batch 7, the vanadium-containing alloy Batch 8 showed higher scatter, see Fig. 14, and hence lower life.

The inferior life with vanadium addition was hypothesized from monotonic properties of both materials. The yield and the tensile strength of the alloy improved with the increase in the total element content in a 2.25Cr-Mo steel. Hence, with the increase in alloy content, modulus (E) and proof strength increased. As strength increased, ductility and % elongation were reduced with alloy content, as shown in Table 27. Under total strain control testing, plastic strain is reduced with the increasing strength achieved by the alloying additions. The saturated stresses at half life in the case of 2.25Cr-Mo-V steel were 50 to 75 MPa higher than in the similar strain ranges for 2.25Cr-Mo steel. As a result, mean stresses were retained and were higher in the case of 2.25Cr-Mo-V steel. Such a behavior was also observed for a titanium alloy (IMI 829) and a superalloy (MAR M 002) under HTLCF, where the plastic strain per cycle reduced and enhanced the mean stresses /24/. The above criterion was valid in 2.25Cr-Mo-V steel, when increased strength resulted in lower plasticity. Retained mean stresses caused life shortening effects. However, compared with the 2.25Cr-Mo system, which has more plastic strains and less mean stresses, 2.25Cr-Mo-V performed inferiorly under HTLCF.

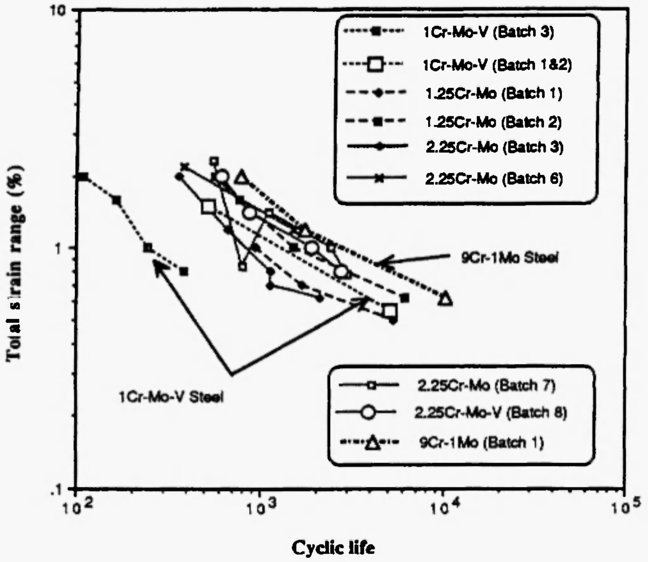


Fig. 13: Effect of composition on the creep-fatigue behavior of low alloy steels.

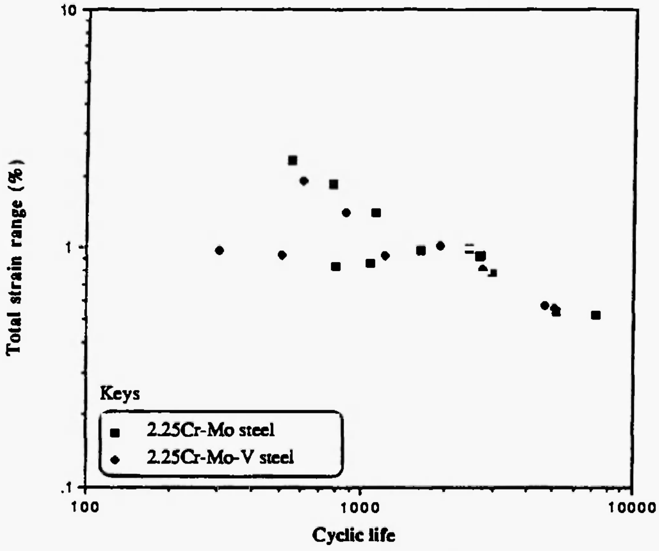


Fig. 14: Effect of vanadium on the creep-fatigue behavior of 2.25Cr-Mo steel.

Table 27

Monotonic properties of 2.25Cr-Mo steels /13/

Alloy	Temperature	YS MPa	UTS MPa	% Elongation
2.25Cr-Mo	RT	470	597	20
-do-	593	305	334	34.5
2.25Cr-Mo-V	RT	620	720	18
-do	593	443	456	26.5

Summary

The following trends were observed:

1. Isolating variations in the materials arising from differences in microstructures, N&T heat treatments and test parameters, such as temperature and strain rate, the creep-fatigue response of low alloy steels improved with the chromium content.
2. Dwell sensitivity of low alloy steels with holds in either the tension or the compression direction was different for different low alloy steels.
3. The addition of vanadium to a standard alloy system, 2.25Cr-Mo, caused a deterioration in high-temperature creep-fatigue response.
4. There was a lack of information on testing and material details in the published data where strain rate, stress relaxation of a hold time, microstructures and differences in heat treatment conditions were unaccounted for.
5. There were limiting values of the test temperature, direction of hold time and strain rate, above which only the life debit associated.

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