Low Cycle Fatigue Strength on Combined Stress Wave of Cast Steel

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1. Introduction

With the recent trend of the increase in output and in size of primemovers, it has become necessary to investigate the thermal fatigue problem concerning the repeated thermal stress wave superposed with high frequency secondary wave. The combustion chamber wall of the large diesel engine is a typical example to the above. This paper reports the results of the experiments mainly about the mutual interference between low cycle fatigue strength and high cycle fatigue strength, i.e. the combined wave fatigue strength.

2. Test material and test conditions

Test material is 0.5 Mo-cast steel which has chemical composition and mechanical properties as shown in Table 1. The test specimens were heat treated as follows; 900° C x 4 H oil quenching, 680° C x 4 H air cooling. The stress wave pattern of these experiments is shown in Fig. 1. The fatigue test conditions are shown in Table 2 and the tests were

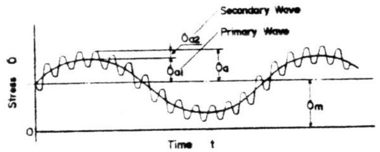

Fig. 1 Test Pattern of Combined Wave Fatigue Test.

Table 1 Chemical Composition and Tensile Properties.

C	Si	Mn	P	S	Mo
0.17	0.41	0.58	0.006	0.015	0.49

Test Temp. (°C)	Yield Stress (kg/mm²)	Tensile Strength (kg/mm²)	True Tensile Strength (kg/mm²)	Elongation (%)	Contraction (%)	Young's Modulus (kg/mm²)
R.T	25.9	50.5	71.3	26.0	37.8	2.1×10^4
300	26.1	55.7	75.7	15.8	30.2	1.9×10^4
500	23.8	45.8	83.1	25.1	60.8	1.6×10^4

Table 2 Test Conditions

Symbols	Test Temp.	Primary Wave	Secondary Wave	Note
R- 1	R.T	—	2000 cpm	High Cycle Fatigue
R- 2		10 cpm	—	Low Cycle Fatigue
R- 3		10 "	2000 " σ_{a2}=16.5	Mutual Interference
R- 4		10 "	2000 " =13.0	Mutual Interference
R- 5		10 "	2000 " =10.0	Mutual Interference
R- 6		10 "	2000 " = 6.0	Mutual Interference
R- 7		10 "	2000 " = 3.0	Mutual Interference
R- 8		2 "	2000 " =10.0	Frequency
R- 9		2 "	400 " =10.0	Frequency
R-10		10 "	2000 " =10.0	Mean Stress
H- 1	500°C	—	2000 cpm	High Cycle Fatigue
H- 2		10 cpm	—	Low Cycle Fatigue
H- 3		10 "	2000 " σ_{a2}=15.0	Mutual Interference
H- 5		10 "	2000 " = 9.0	Mutual Interference
H- 8		2 "	2000 " = 9.0	Frequency
H- 9		2 "	400 " = 9.0	Frequency

conducted under constant stress amplitude with tension compression stresses.

The gauge part of each specimen is a solid cylinder of 11 mm diameter and 40 mm length.

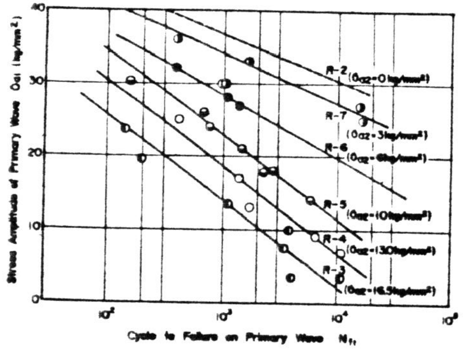

Fig. 2 Test Results of Combined Wave Fatigue Test (R.T)

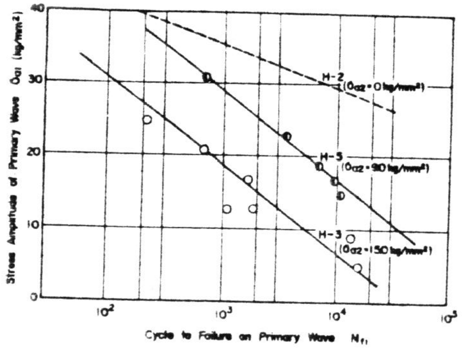

Fig. 3 Test Results of Combined Wave Fatigue Test (500°C)

3. Experimental results and discussion

3.1 The effect of mutual interference

The fatigue limit at Room Temperature (R-1) was 16.5 kg/mm^2, and at 500° C (H-1) was 15.0 kg/mm^2. The results of combined stress wave fatigue tests are shown in Fig. 2 and Fig. 3. From these figures, it can be seen that fatigue strength considerably decreases when secondary wave stress amplitude on primary stress wave exists. On the other hand, these data, when rearranged with max. stress amplitude σ_a , show that there are noneffective stress amplitude of secondary wave[(1)(2)] which

Table 3 Calculation Results of Fatigue Damage (1 Primary cycle)

		Test Results		Miner's Law					Corten-Dolan
		D Test	N Test	D High	D Low	D Total	N pred.	D Test / D Total	b (gradient) ($S^bN=C$)
R.T	σ_{a2}=16.5, σ_{a1}=20	3.33×10^{-3}	3.0×10^{2}	1.74×10^{-4}	9.52×10^{-4}	1.13×10^{-3}	8.88×10^{2}	2.96	6.1
	σ_{a1}=10	4.77×10^{-4}	2.1×10^{3}	4.02×10^{-5}	2.22×10^{-5}	6.24×10^{-5}	1.60×10^{4}	7.63	5.5
	σ_{a2}=13.0, σ_{a1}=20	1.28×10^{-3}	7.8×10^{2}	1.62×10^{-5}	2.70×10^{-4}	2.86×10^{-4}	3.50×10^{3}	4.48	4.0
	σ_{a1}=10	1.85×10^{-4}	5.4×10^{3}	5.50×10^{-6}	6.90×10^{-6}	1.24×10^{-5}	8.07×10^{4}	1.49×10	2.6
	σ_{a2}=10.0, σ_{a1}=20	5.55×10^{-4}	1.8×10^{3}	2.06×10^{-6}	9.09×10^{-5}	9.30×10^{-5}	1.08×10^{4}	5.98	3.3
	σ_{a1}=10	7.70×10^{-5}	1.3×10^{4}	9.69×10^{-7}	2.33×10^{-6}	3.30×10^{-6}	3.03×10^{5}	2.34×10	1.8
	σ_{a2}=6.0, σ_{a1}=20	1.09×10^{-4}	9.2×10^{3}	1.46×10^{-7}	2.04×10^{-5}	2.05×10^{-5}	4.87×10^{4}	5.30	2.6
	σ_{a1}=10	7.70×10^{-6}	1.3×10^{5}	1.06×10^{-7}	5.41×10^{-7}	6.47×10^{-7}	1.55×10^{6}	1.15×10	1.8
	σ_{a2}=3.0, σ_{a1}=20	6.91×10^{-6}	1.4×10^{5}	1.51×10^{-8}	6.90×10^{-6}	6.91×10^{-6}	1.44×10^{5}	1.00	12.2
	σ_{a1}=10	2.00×10^{-7}	5.1×10^{6}	1.16×10^{-8}	1.85×10^{-7}	1.97×10^{-7}	5.09×10^{6}	1.02	12.2
500°C	σ_{a2}=15.0, σ_{a1}=20	1.25×10^{-3}	8.0×10^{2}	2.067×10^{-4}	8.33×10^{-4}	1.04×10^{-3}	9.62×10^{2}	1.20	—
	σ_{a1}=10	1.78×10^{-4}	5.6×10^{3}	4.644×10^{-5}	1.67×10^{-5}	6.31×10^{-5}	1.58×10^{4}	2.83	—
	σ_{a2}=9.0, σ_{a1}=20	1.79×10^{-4}	5.6×10^{3}	8.21×10^{-7}	7.69×10^{-5}	7.77×10^{-5}	1.29×10^{4}	2.31	8.4
	σ_{a1}=10	2.63×10^{-5}	3.8×10^{4}	3.32×10^{-7}	1.43×10^{-6}	1.76×10^{-6}	5.68×10^{5}	1.49×10	3.3

has no influence to fatigue strength of combined stress wave fatigue. This noneffective stress amplitude of secondary wave at 500° C is greater than that at Room Temperature. Authors examined several kinds of calculation methods by which the fatigue strength on the combined waves were predicted. The results of these calculations are shown in Table 3.

(1) Linear damage law

The damage by low cycle fatigue is presumed by max. stress amplitude σ_a from the results of experiment R-2 and H-2. The damage by high cycle fatigue is presumed from the results of experiment R-1 and H-1 by considering the effect of primary stress wave as mean stress, using modified Goodman's method. The effect of mean stress was calculated by dividing one primary wave cycle in 36 blocks. In this way the life to fatigue failure was evaluated based upon the above two damages using Miner's law.

(2) Corten-Dolan law

The damage by primary and secondary stress wave was calculated by modifying the gradient of S-N diagram (R-1, H-1). The calculated gradient of S-N diagram was shown in Table 3 as most compatible value.

(3) Yamada and Kitagawa's law[(3)(4)]

A peak pair method was used for this assumption, and the combined stress waves were replaced with the stress pattern of the repeated

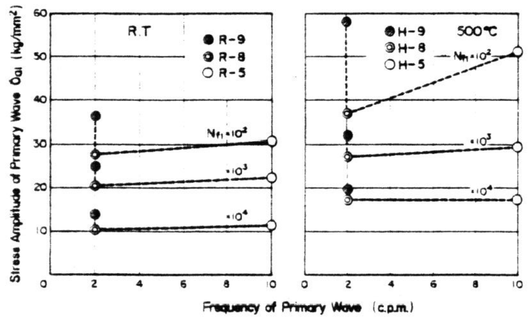

Fig. 4 Effect of Primary and Secondary Frequency

stress amplitude varing sinusoidally with zero mean stress.

3.2 The effect of frequency

The effect of frequency of primary and secondary waves is shown in Fig. 4. The fatigue strength for frequency ratio 200 and 1000 is more effective at 500° C than at Room Temperature. The effect of frequency upon the long fatigue life zone is rather little at both temperatures. These phenomena cannot be explained clearly by the above fatigue damage calculation only.

3.3 The effect of mean stress

Experiments were made with mean stress value 10 kg/mm^2 and 20 kg/mm^2 (R-10). The test results are shown in Fig. 5. From the figure, it became clear that the effect of mean stress to combined stress wave fatigue could be treated in line with Goodman's diagram and the cross point of abscissa denotes tensile strength.

3.4 Micro-structure of failed surface

The caterpillar patterns detected at high cycle fatigue (R-1), low cycle fatigue (R-2) and combined stress wave fatigue (R-3) are shown in Fig. 6 (omitted herein). Such pattern as above could not be found in the fatigue failed surface of 500° C test.

4. Conclusion

Characteristics of fatigue strength of the material subjected to the high cycle and low cycle fatigue were examined in relation to the damages by mutual interferences of two combined stress waves,

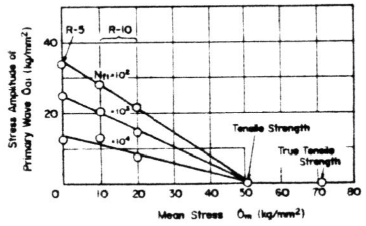

Fig. 5 Effect of Mean Stress of Combined Wave Fatigue.

frequencies, test temperatures, and mean stresses. From the above examination, it was concluded that the fatigue life by combined stress wave fatigue should not be evaluated by the damage of low cycle fatigue or high cycle fatigue separately, because either one of them cannot explain independently the characteristics of noneffective secondary stress amplitude and effect of frequencies, etc. Therefore the predicting method of fatigue life by combined stress wave fatigue should be established considering the behavior of strain as cycle dependent stress relaxation[5][6].

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