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HIGH TEMPERATURE FATIGUE BENDING PROPERTIES OF LOW CARBON STEEL

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ABSTRACT

High temperature fatigue bending properties of low carbon steel was studied. Tests were carried out on a constant speed of 50Hz (3000rpm) at 300°C and 500°C by decreasing stress amplitudes. The investigation was performed based on the stress-life (S-N) approach for high cycle fatigue regime, to establish the empirical equations for fatigue strength and endurance limit.

The endurance limit for 300°C is 249.9MNm^{-2} with knee at 10.03 million cycles while for 500°C it is expected to occur on 171.0MNm^{-2} at 43.29 million cycles. For low carbon steel test at even higher temperature will experience further drastic drop in fatigue strength.

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INTRODUCTION

Fatigue failures are sometimes disastrous and caused damages in properties as well as possible loss of innocent lives. It is estimated that about 90% of metal failure were due to this phenomenon.

In year 1954 two British commercial passenger jet aircrafts (British Comet) were fatally crashed as a result of the failure of the fuselage, and in year 1988, a Hawaiian Airline's Boeing 737 lost one-third of its cabin top while in flight at 25,000 feet. Both were due to the fatigue of the metal [1]. There are also several major industrial accidents went unreported besides hundreds of minor accidents happen every day in all sorts of sector due to the same cause.

It is a fact that all failures or accidents incurred costs. According to a comprehensive study, the cost of fracture of materials in the United States in 1982 was around US$100 billion or about 4% of the gross national product of that year [2]. This staggering figure was considered significant and directly affecting the economy of the country. If metal especially steel, continue to fail as a result of fatigue, the amount of money wasted keep on increasing as more and more of this material is being utilized.

The most common steel is low carbon steel or widely known as mild steel, which generally contains less than 0.25% carbon. It is considered as general-purpose steel and is used where hardness and tensile strength are not the most important requirements [3]. As the utilization is very vast, in some applications mechanical parts made of low carbon steel are not only subjected to static or cyclic stresses but also to high temperature condition. Parts in vehicle engine are operating at a temperature around 300°C and parts in power plant are operating at the average temperature of 500°C.

Temperature is one of the major factors that affect the fatigue characteristic or specifically the fatigue strength of low carbon steel or any other materials.

The method to determine fatigue strength of any mechanical parts that are subjected to cyclic stresses depends on the nature or the intended purpose of their utilization. The stress-life (S-N) approach is most suitable in common applications, which require live span of the parts to fall in high-cycle fatigue (HCF) region, compared to the strain-life (ε-N) and the linear-elastic fracture mechanics (LEFM) approaches, which are focusing on low-cycle fatigue (LCF) domain.

In this paper, a study of high temperature fatigue bending properties of low carbon steel based on the stress-life (S-N) approach is presented.

MATERIALS AND EXPERIMENTAL

Material

Material for specimens were prepared according to the standard size for high temperature testing as shown in Fig. 1 with the average surface roughness between 0.025 to 1.6 micron.

Test and Test Parameter

Tests were carried out on Ono’s High Temperature Rotary Bending Fatigue Testing Machine, model H7, manufactured by Shimadzu Corporation by controlling three major parameters namely speed, temperature and stress amplitude which depend on load.

The specification for the speed of the machine is between 28.3Hz and 56.7Hz. Since it is recommended that testing speed to be set at one selected value typically between 25 to 100Hz [4] it was arbitrarily chosen at 50Hz (3000rpm).

In order to obtain two sets of results that are relevant to the actual application of the material, testing temperature were set at 300°C and 500°C. The temperature settings capability of the furnace is from 300°C to 850°C.

The numbers of specimens tested at set temperatures were seven and eight respectively i.e. one specimen for each stress amplitude.

Stress amplitudes were calculated based on the R. R. Moore Rotating Beam Test concept shown in Fig. 2 [5] as the machine is built on the same concept.

$$\sigma = \frac{16WL}{\pi d^3}$$

where the distance between load supporting points, $L = 20cm$, and

the diameter of specimen, $d = 0.8cm$

The amplitudes that give the number of cycles to failure were gradually decreased until the test showing the evidence for endurance limit is achieved (specimen does not break after stipulated endurance for 10 million cycles).

The respective fatigue strength of any cycle prior to the knee of endurance limit could be obtained using the equation that defined the S-N curve.

Estimating the Fatigue Strength

The equation to be used allowed the estimated finite life, N to be found for any fully reversed fatigue strength, S_n or the estimated strength can be found for any N. Research have shown that high cycle fatigue (HCF) data are rectified by a logarithmic transform to both stress and cycles to failure [6]. For HCF regime is concerned with failure from 10^3 cycles onwards and hence material strength, S_m is being taken at 10^3.

For material with endurance limit, $S_n = S_e$ while for material that does not exhibit endurance limit knee, the fatigue strength is taken at certain number of cycles. According to Juvinall and Marshek [7], test data indicate that the estimate for bending type of loading is

For bending, $S_m = 0.9S_{ut}$ (1)

Fatigue strength at any N, $S_n = aN^b$ (2)

$$\log S_n = \log a + b \log N$$

$$b = \frac{1}{z}\log\left[\frac{S_m}{S_e}\right]$$

where $z = \log N_1 - \log N_2$

$$\log a = \log S_m - b \log N_1$$

$$\log a = \log S_m - 3b$$

since $N_1 = 1000$

N_2 is taken at knee of endurance limit or specified fatigue strength.

RESULTS AND DISCUSSION

Characteristics from Empirical Data

Rotating bending fatigue strength, S_f and tensile strength, S_{ut} of low carbon steel shown in Table 1 is derived from Fig. 3 since the tabulated values are not available. These curves were produced by Allen and Forrest [8] and could be reliably use as a basis for comparison and analysis.

It can be seen that there are increases of fatigue strength and tensile strength at 300°C compared to room temperature properties due to strain ageing effect as well as reduction in ductility [9]. Even though tensile strength is increased by 16.1%, long endurance fatigue strength at 100 million cycles recorded a remarkable increased of 34.9% compared to room temperature application. But at 500°C, both tensile and fatigue strength drop substantially.

Notice that at 300°C, between large difference of 5×10^5 and 10^8 cycles, there is no remarkable drop (only 10.0MNm^{-2}) in the fatigue strength due to the capability of fatigue resistance and increase of hardness of low carbon steel at that temperature. Thus it is quite reasonable to take the endurance limit as 340.0MNm^{-2}.

As a matter of concern, fatigue strength in Table 1 is not equivalent to the results of testing because both were carried out at different speed i.e. 33Hz and 50Hz. This is due to the fact that frequency is also one of the factors affecting the fatigue strength at elevated temperature.

However the difference in speed is only 17Hz and hence should not be having substantial effect on fatigue strength value and could be roughly taken as an approximation for comparison purposes. For instance, empirical value from fatigue test on low carbon steel at room temperature in three different frequencies i.e. at 25Hz, 167Hz and 500Hz, resulted in endurance limit at 215.0MNm^{-2}, 215.0MNm^{-2} and 230.0MNm^{-2} respectively [4]. It can be seen that there are no changes for even a 142Hz increase. Therefore even though the testing was carried out at elevated temperature the effect for difference of 17Hz on fatigue strength would be considered as negligibly small.

Characteristics at Temperature 300°C

The result from isothermal testing at 300°C is tabulated in Table 2, its S-N curve is shown in Fig. 4, and the comparison of fatigue strengths with the empirical values is given in Table 3.

In agreement with the natural trend of fatigue bending properties, the curve shows the number of cycles to failure or fatigue life, increased logarithmically as the loading or nominal stresses are being lowered until the endurance limit.

The estimated fatigue strength of the empirical data at 10 million cycles is 354.4MNm^{-2}. It deviates slightly from the ideal value between 340.0MNm^{-2} and 350.0MNm^{-2}. This shows that Eq. 2 might not be a good estimate for very high cycle domain, as the relationship becomes not linear. Hence the fatigue strength at 10 million cycles is being arbitrarily estimated at 345.0MNm^{-2} for comparison purposes.

From the curve it can be seen that the endurance limit or knee can be estimated after 10 million cycles. It is a reasonable estimation since for steel the specimen is not expected to fail after 10 million cycles [4]. Furthermore from the empirical data (Table 1) there is only a 10.0MNm^{-2} difference in fatigue strength between 5×10^5 and 10^8 cycles and therefore the endurance limit shall exist somewhere between these two values.

The equation that defined the S-N curve is applicable up to 10.03 million cycles according to a knee value at 249.9MNm^{-2}. The fatigue strength at 5×10^5 and 10 million cycles are 15.4% and 27.5% respectively lower than the empirical data.

Characteristics at Temperature 500°C

The result from isothermal testing at 500°C is tabulated in Table 4, the S-N curve of the test is shown in Fig. 5, and the comparison of fatigue strengths with the empirical values can be seen in Table 5.

The estimated value of the empirical data at 10 million cycles is 213.1MNm^{-2}. It is acceptable as it falls between 180.0MNm^{-2} and 250.0MNm^{-2}.

Ironically comparison made at 5×10^5 cycles shows a better fatigue strength value compared to empirical data. One of the causes is that, the empirical data were obtained from numerous repeated testing whereas the current test is only a single test and hence less accurate in term of spread of data.

The endurance limit knee at this temperature is expected to occur at higher cycles due to increased of temperature, which has weakened the strength and fatigue resistance of specimen. Furthermore at higher temperature (comparing 300°C and 500°C) the formation of oxide film and oxidation phenomenon occurs at faster rate. The investigation made on first five specimens tested (refer Table 4) have shown formation of oxide film but an unbroken specimen stop at 755,200 cycles have shown oxidation and so did the rest of specimens with higher cycles. Obviously oxidation is prevalent at higher temperature and longer cycles or time due to increase chemical reaction rate.

From Fig. 5, it can be seen that S-N curve plotted is well fitted among the points and the scatter is visibly smaller from the curve. Since there is an empirical value (from past researchers, Table 1) of 180.0MNm^{-2} the extrapolation was done to 100 millions cycles for comparison purposes. Based on empirical equation $y = -22.964 Ln(x) + 574.79$ the extrapolated value at 100 millions cycles is 151.7MNm^{-2}, which seems to be quite far away from 180.0MNm^{-2}. This lead to the conclusion, endurance limit's knee occurred somewhere between 10 million to 100 million cycles region.

In view of the fact that comparison made on fatigue strengths showed a close relationship between empirical and actual data, it could be confidently assumed that the endurance limit of actual test is close to the empirical data. By taking 5% of possible error from the empirical value, the endurance limit calculated is 171.0MNm^{-2} at 43.29 millions cycles.

Changes of Characteristics from 300°C to 500°C

By and large, the patterns on both S-N curves show larger difference as the testing moving towards infinite cycles. Unlike the characteristics of empirical data (which is shown by Table 1), the reduction of fatigue strength from 300°C to 500°C, were smaller. This is due to the fact that, the actual S-N curve at 300°C is shifted down or has overall lower fatigue strength than predicted due to the reasons mentioned earlier. Whereas the actual S-N curve at 500°C is relatively closer to the empirical curve obtained. Hence the gap between both curve become smaller and the difference of fatigue strength between them are smaller. In short, the results achieved for 500°C tests were more accurate than 300°C tests.

From the results of present investigation, it is concluded that the fatigue strength in an isothermal condition decreases with temperature rise. Another noticeable phenomenon at both conditions is that the life of the low carbon steel increased remarkably as the stress amplitude decreased especially near to the endurance limit. For shorter cycle's application such as below one million cycles, the fatigue strength for respective cycle's concept must be used as a basis for design and hence the stress applied can be increased rather than just based on the endurance limit. At a very high cyclic rate of loading it is of course necessary for design engineer to use the endurance limit at the respective operating condition for more reliable application.

Fig. 6 shows the comparison among two S-N curves.

CONCLUSION

In both cases the S-N curves demonstrated a general characteristic for low carbon steel with existence of endurance limit. The endurance limit for 300°C is 249.9MNm^{-2} with knee at 10.03 million cycles onwards while for 500°C it is expected to occur on 171.0MNm^{-2} at 43.29 million cycles.

Obviously at higher temperature such as 500°C, low carbon steel is softened and has lower fatigue resistance. It is expected that, for low carbon steel test at even higher temperature will experience further drastic drop in fatigue strength. Furthermore the existence of knee for endurance limit also occurs at later stage. On the basis of the results obtained, it is concluded that the fatigue strength in an isothermal condition decreases with temperature rise. In general, the life of the low carbon steel increased remarkably as the stress amplitude decreased especially near to the endurance limit for both cases.

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Table 1. Rotating bending fatigue strength, S_f and tensile strength, S_{ut} of low carbon steel at 33Hz

Temperature (°C)	**Fatigue Strength, S_f (MNm^{-2}) at cycles to failure**			**Tensile Strength, S_{ut} (MNm^{-2})**
	$N_f = 5.0 \times 10^5$	**$N_f = 1.0 \times 10^7$**	**$N_f = 1.0 \times 10^8$**	
25	290.0	278.9	252.0	465.0
300	350.0	345.0	340.0	540.0
500	250.0	213.1	180.0	300.0
% of changes from 25°C to 300°C	20.6	23.7	34.9	16.1
% of changes from 300°C to 500°C	-28.5	-38.2	-47.0	-44.4

Table 2. Comparison between fatigue strength of empirical data and result obtained for testing at 300°C.

Temperature (°C)	**Fatigue Strength, S_f (MNm^{-2}) at cycles to failure**	
	$N_f = 5.0 \times 10^5$	**$N_f = 1.0 \times 10^7$**
Empirical data	350.0	345.0
Actual	296.5	265.0
% of changes from empirical data	-15.3	-23.1

Table 3. Comparison between fatigue strength of empirical data and result obtained for testing at 500°C.

Temperature (°C)	**Fatigue Strength, S_f (MNm^{-2}) at cycles to failure**	
	$N_f = 5.0 \times 10^5$	**$N_f = 1.0 \times 10^7$**
Empirical data	250.0	213.1
Actual	273.5	204.7
% of changes from empirical data	-9.4	-3.9

Table 4. Results from isothermal testing at 500C.

No.	**Loading**		**No. of cycle (Nf)**	**Duration (min)**	**Remark**
	MNm^{-2}	**kg**			
1	353.240	18.508	16500	8	
2	312.256	16.000	68500	25	
3	302.654	15.508	154500	55	
4	292.740	15.000	150300	50	
5	283.138	14.508	485700	165	
6	264.300	13.508	1308400	435	
7	214.676	11.000	5204000	29 hrs	
8	199.139	10.204	10000065	56 hrs	Halted and unbroken

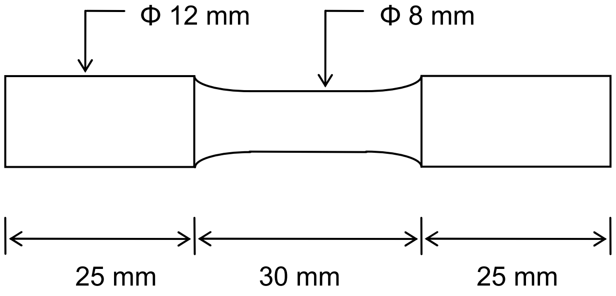

Fig. 1. Specimen for high temperature testing

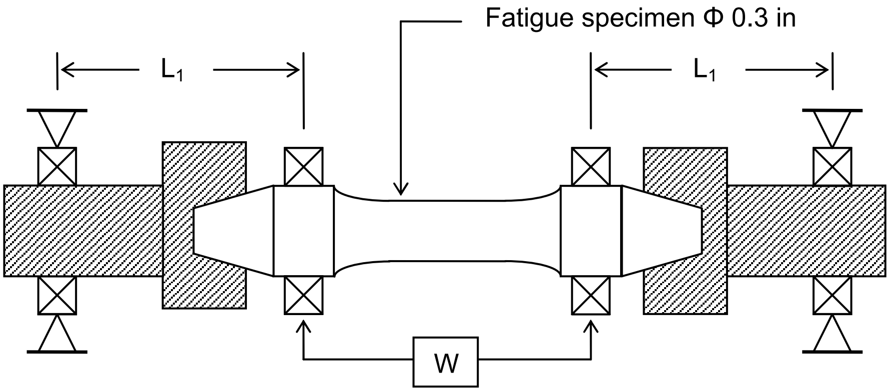

Fig. 2. Schematic diagram of typical R. R. Moore rotating beam test (Budynas, 1999).

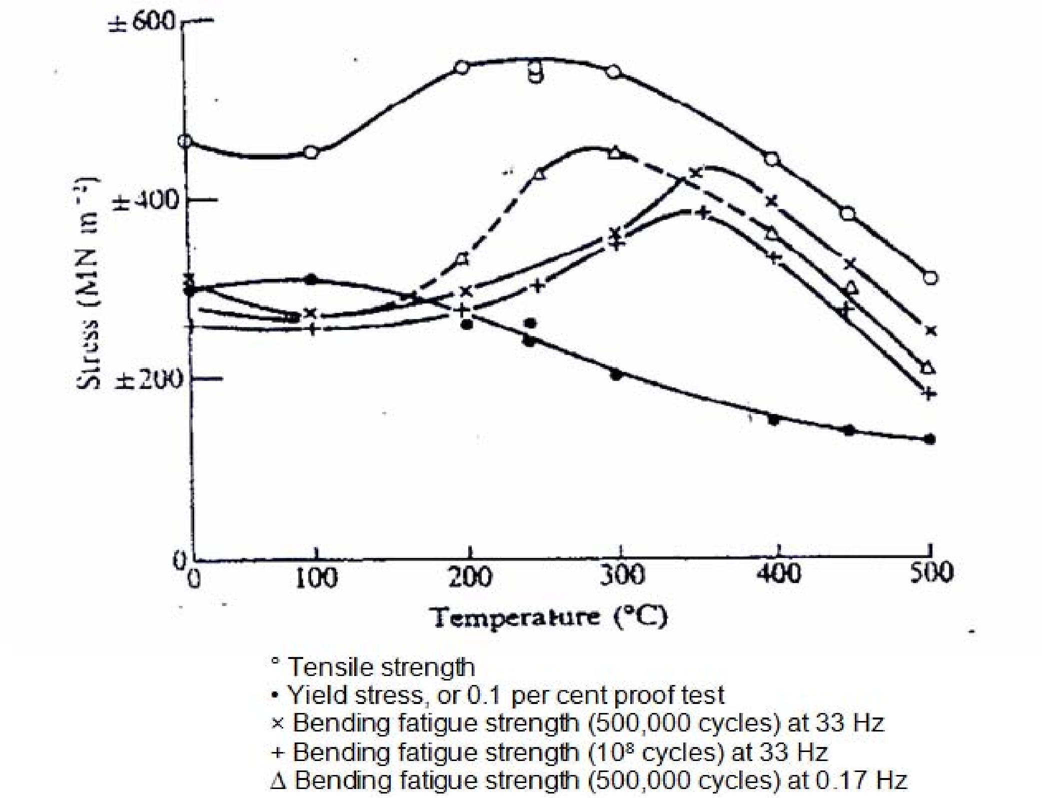

Fig. 3 Effect of temperature on the tensile strength and rotating bending fatigue strength of low carbon steel

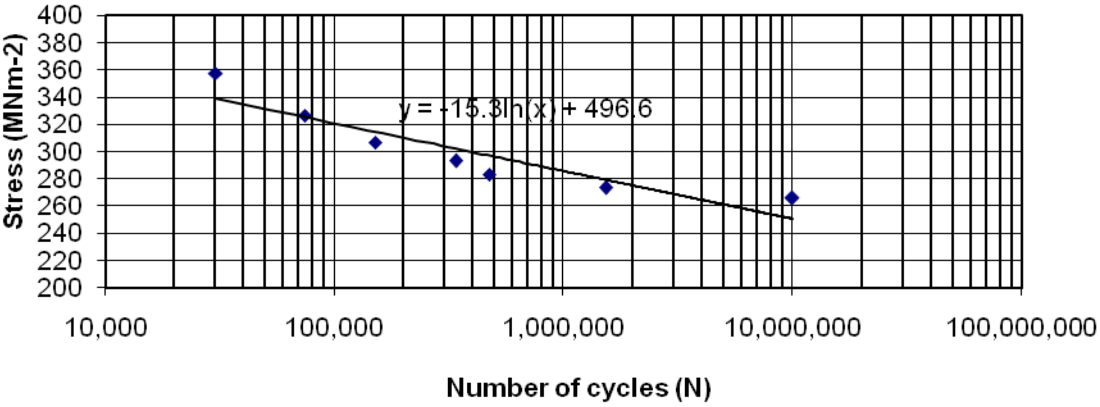

Fig. 4. S-N diagram for low carbon steel specimens at isothermal 300C test.

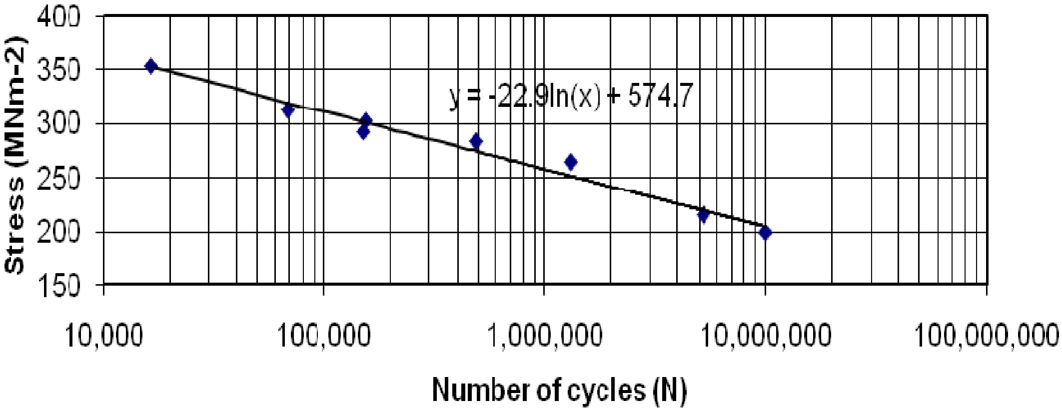

Fig. 5. S-N diagram for low carbon steel specimens at isothermal 500C test.

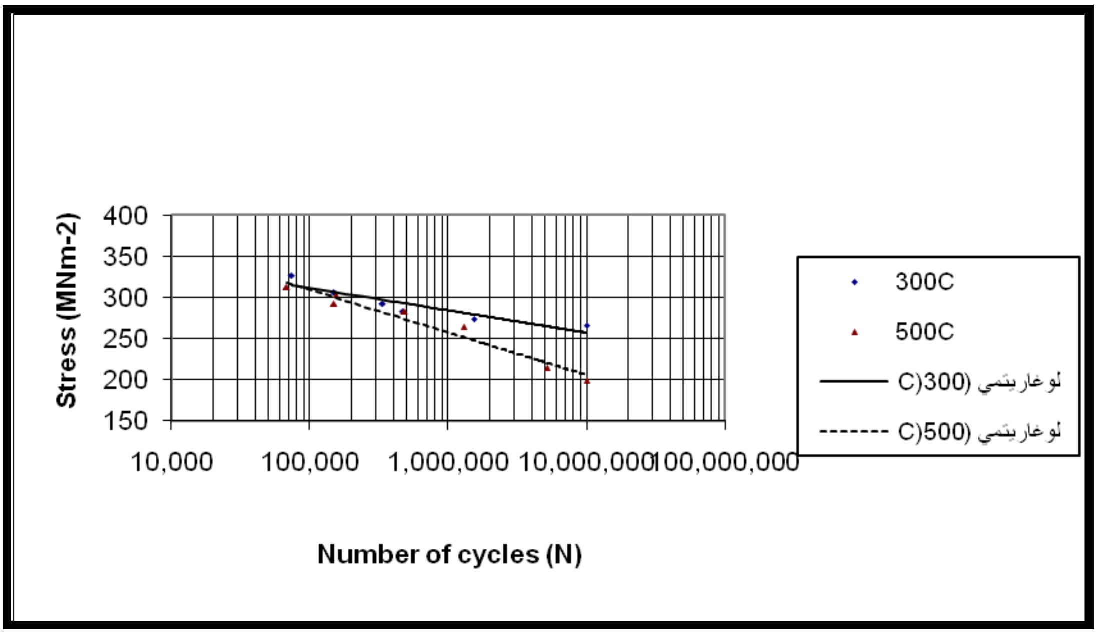

Fig. 6. Comparison of S-N diagram for low carbon steel specimens at isothermal 300C and 500C.