Elastic Hysteresis Property of Several Steels under Fatigue Load

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By

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(Received September 21, 1964)

Observations were made on the plastic strain amplitude on five sorts of carbon steel when they were subjected to the alternating stress. The behaviour of the plastic strain occurring in the specimen of respective steel were compared to each other, and some patterns of variations were stipulated referring to the carbon content. Linear relations between the plastic strain, as well as the hysteresis energy, and the number of cycles to failure were confirmed to hold excepting the case of 0.25% carbon steel. Stress-strain relations under repeating stress were discussed in detail to a certain extent.

1. Introduction

When the repeating load is applied to metallic material, some magnitude of plastic strain actually occurs in the material in each stress cycle, even if the applied stress is relatively small and at the vicinity of the endurance limit. Therefore, in each stress cycle, so-called hysteresis loop in the stress-strain diagram could be obtained, when the observation was made using the suitable technique. The area of this loop is an elastic hysteresis energy and it represents the work done by the external system to the unit volume of the material in each cycle. Although most of thus accumulated energy may turn into heat and be lost to the atmosphere, a certain fraction may actually be stored in the material and associated with the progress of fatigue failure.

The authors have previously developed a fine measuring instrument which amplified the extension and contraction of the specimen subjected to the axial repeating load more than 2,000 times by the optical method, and made some observations on the behaviour of the strain occurring in the specimen under such load[1,2]. From these experiments, the relation $\varepsilon_p \cdot N^{\alpha}=K$ was found to hold between the plastic strain amplitude ε_p and the number of cycles to

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failure N with two constants a & K. This relation is as same as those said to exist in the tests such as thermal fatigue test and plastic fatigue test which is concerned with the failure under very large stress amplitude and with short endurance[1-7]. Furthermore, the hysteresis energy seemed to have an important role in the fatigue failure, since it was found that when the hysteresis energy was plotted against the number of cycles N, the results of two kinds of steel showed a good agreement with each other and gave a linear relation of both variables on the log-log paper.

This investigation was planned to affirm these points by using five kinds of carbon steel whose carbon contents are ranging from 0.14% to 0.71%. The experiments were carried out in the same way as those of the previous ones. There was observed a distinct difference between the behaviours of plastic strain amplitude of the low carbon steels and those of the high carbon steels. Generally speaking, however, the mode of the plastic strain amplitude was rather smooth and converged to certain final value with stress repetitions, corresponding to the stress level. One exception was seen in the case of 0.25% carbon steel which showed a quite different and very complicated behaviour of the plastic strain amplitude through the test period, and this phenomenon seemed to offer us a subject of more detailed investigation in the future. For the other steels, there existed a linear relationship between ε_p and N when two variables were plotted on the log-log paper. A similar relationship was found when the hysteresis energy was taken instead of the plastic strain amplitude, but no agreement of these lines were obtained. Some discussions were also made on the stress-strain curves under repeating load.

2. Materials and Testing Procedures

Five kinds of carbon steel were used for this investigation. Three of them belong to low carbon steel and the rest to high carbon steel. Their chemical compositions are shown in table 1. These materials were carefully

Table 1. Chemical composition of materials.

Material	Chemical composition (%)				
	C	Si	Mn	P	S
0.14% carbon steel	0.14	0.29	0.54	0.015	0.013
0.25% carbon steel	0.25	tr	0.38	0.013	0.027
0.27% carbon steel	0.27	0.26	0.65	0.046	0.029
0.58% carbon steel	0.58	0.17	0.82	0.036	0.031
0.71% carbon steel	0.71	0.28	0.20	0.024	0.006

Table 2. Heat treatment and mechanical properties of materials.

Material	Heat treatment	Upper yield point σ_{SO} (kg/mm²)	Lower yield point σ_{SU} (kg/mm²)	Ultimate strength σ_B (kg/mm²)	Breaking strength on final area σ_T (kg/mm²)	Elong-ation φ (%)	Reduc-tion of area ψ (%)	Young's modulus E (kg/mm²)
0.14% carbon steel	810°C 1 hr. F.C.	25.8	23.6	40.1	93.8	44.9	71.0	2.11 $\times 10^4$
0.25% carbon steel	875°C 1 hr. F.C.	33.4	28.7	51.1	87.1	38.4	54.0	2.14
0.27% carbon steel	830°C 1 hr. F.C.	27.7	21.2	37.8	73.3	20.1	62.3	2.14
0.58% carbon steel	800°C 1 hr. F.C.	34.6	34.2	71.2	98.1	25.0	32.9	2.03
0.71% carbon steel	760°C 1 hr. F.C.	31.9	30.4	65.4	100.0	25.6	36.8	2.10

machine-finished after full annealing. Table 2 gives the annealing conditions and the mechanical properties of the materials. Although there was some difference in the contents of the elements other than carbon between each steel, and there was little systematic relation between the carbon content and the annealing temperature or static strength, we disregarded these points, since this investigation was aimed at observing the behaviours of the plastic strain amplitude under repeating load for various kinds of materials.

Specimens shown in Fig. 1 were used in the experiments. The diameter of the test portion is 4.5 mm only for 0.14% carbon steel, but it is 5 mm for the other steels.

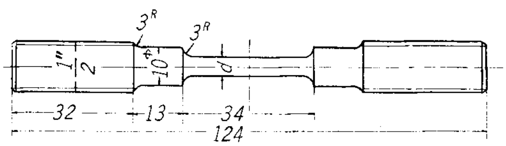

Fig. 1. Test specimens.

The experiments were carried out under the condition of completely reversed repeating axial load with Haigh fatigue testing machine. The strain measuring instrument was attached to respective specimen and the total strain amplitude was measured through the test preriod. The instrument has been described in detail in the previous papers, so that no explanation might be needed here. It is only remarked that in the subsequent discussions, stress σ denotes the alternating stress amplitude: plastic strain ε_p denotes the plastic strain amplitude obtained by subtracting the elastic strain amplitude from the measured total strain amplitude and therefore ε_p corresponds to the half width of the hysteresis loop on the strain axis: and hysteresis energy W denotes $4\sigma \cdot \varepsilon_p$, which is considered to be proportional to the area of the loop on the assumption that the shape of the loop remains constant through the period.

3. Results and Discussions

Fatigue strength of each steel is given in Fig. 2. The 0.58% carbon steel has the highest strength of all, which is followed by the 0.27% carbon steel. The 0.71% carbon steel and the 0.25% carbon steel have medium strength.

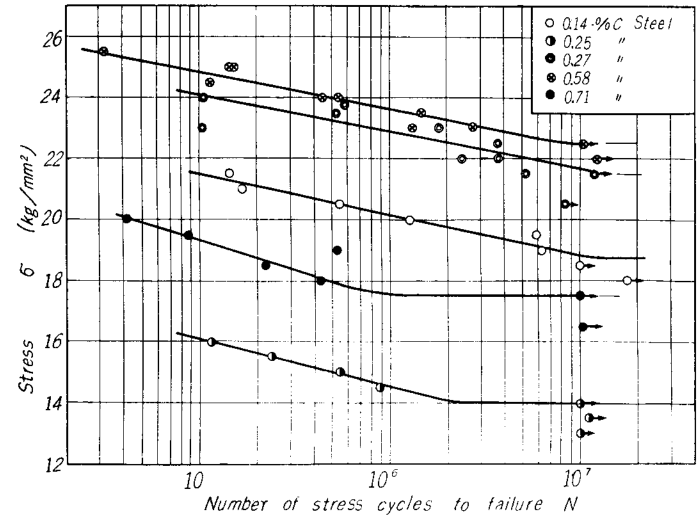

Fig. 2. Stress vs. stress cycles to failure.

The strength of the 0.25% carbon steel remains at an unexpectedly low level and this fact seems to be associated with an unusual and complicated behaviour of the plastic strain of this steel, which is quite different from those of the other steels, as discussed below.

Results of strain measurement are given in Figs. 3, 4 and 5 for 0.14%, 0.25%

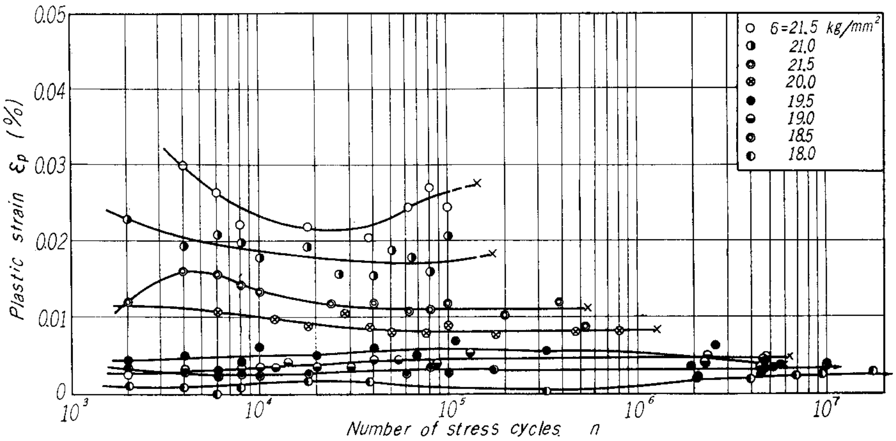

Fig. 3. Plastic strain vs. stress cycles. 0.14% C steel.

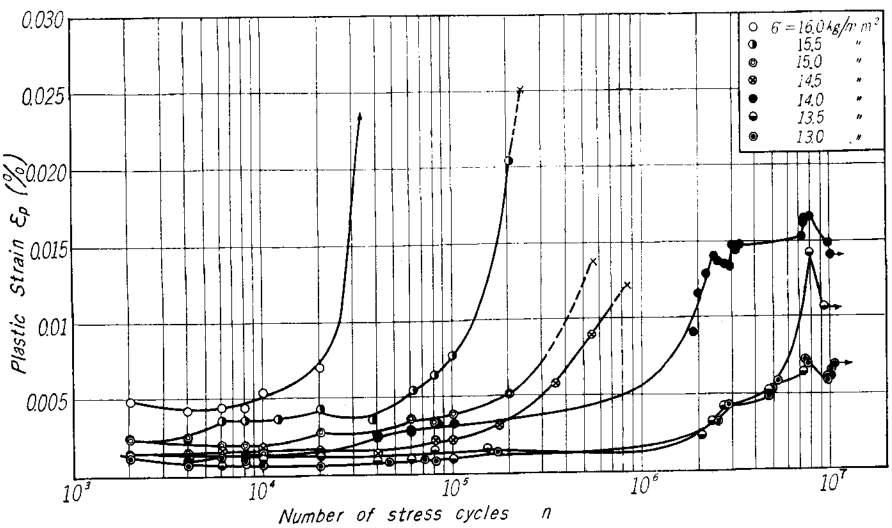

Fig. 4. Plastic strain vs. stress cycles. 0.25% C steel.

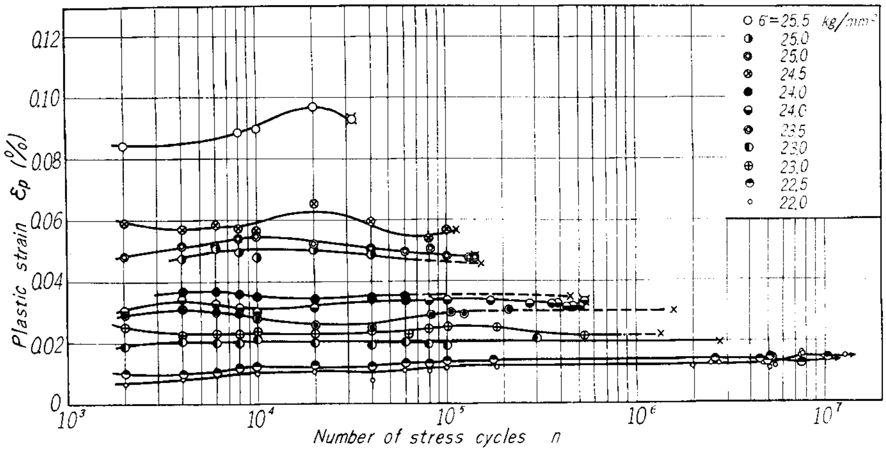

Fig. 5. Plastic strain vs. stress cycles. 0.58% C steel.

and 0.58% carbon steel respectively, by plotting the plastic strain ε_p against the number of cycles n. The plastic strain of 0.27% carbon steel is almost the same as that of 0.14% carbon steel in its magnitude and its mode of variation, and the plastic strain of the 0.71% carbon steel is not so different from that of 0.58% carbon steel in its magnitude and its mode of variation. Except in the case of 0.25% carbon steel, the low carbon steels reveal a somewhat larger variation of plastic strain at the initial period of the test than the high carbon steels. Generally speaking, the plastic strain of the low carbon steels increases first and attains certain extreme value after several thousands of cycles, and then decreases gradually to certain final value and remains at that value through the other period of the test. On the other hand, the high carbon steels do not show a large variation of the plastic strain, but the magnitudes of the plastic strain are evidently larger than those of the low carbon steels.

The 0.25% carbon steel, in spite of the fact that it belongs to the low carbon steel based on its carbon content, gives a quite different behaviour of plastic strain from the other steel. As shown in Fig. 4, the magnitude of strain is very small in the initial stage, that is, if the comparison is made by taking the specimens which fractured after about 5.5×10^5 stress cycles for instance, the plastic strain of 0.25% carbon steel is about one-eighth of that of 0.14% carbon steel, and is about one-fourteenth of that of 0.58% carbon steel. The plastic strain of that steel then increases gradually with increasing stress cycles, but the mode of the increase is not uniform nor continuous, and sometimes a slight decrease was observed after a rather sudden increase. The phenomenon is more clearly observed from Fig. 6, which was plotted by taking the logarithm of the plastic strain against the ratio of stress cycles n to the stress cycles to failure N, and therefore $n/N=100\%$ represents the total life for fractured specimens and 10^7 stress cycles for unbroken ones. The plastic strain of the specimen tested with the stress of 16.0 kg/mm², as indicated in Fig. 6 in its whole figure, and only partly in Fig. 4, showed a sudden increase attaining to about 0.09% at about 35% of the total life and then remained almost constant after a slight decrease. It might be thought that these unusual strain behaviours of the 0.25% carbon steel is associated with a larger difference of the upper and lower yielding points of this steel than those of the other steels as

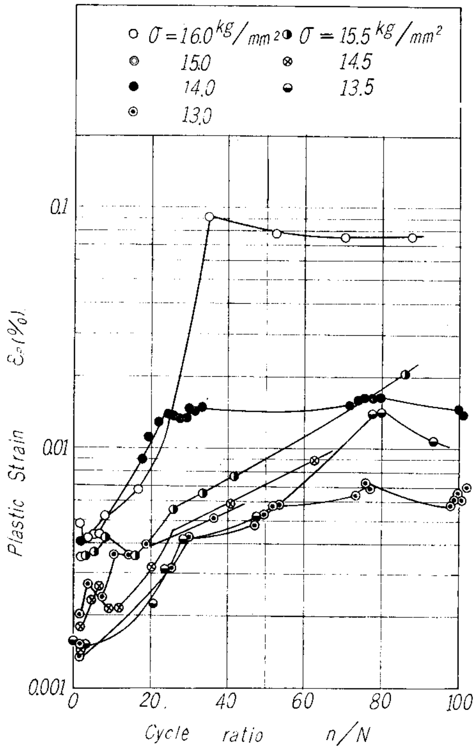

Fig. 6. Plastic strain vs. cycle ratio. 0.25% C steel.

shown in Table 2, although any more detailed examination was not attempted in this investigation.

With respect to the plastic strain of the other four steels, its magnitude is approximately constant almost all through the test period, even if it reveals some variation in the initial stage. Therefore, as in the previous investigations, the plastic strain ε_p at 50% of the total life was taken up as the representative value of the plastic strain of each specimen, and the following discussions were made based on this value of ε_p.

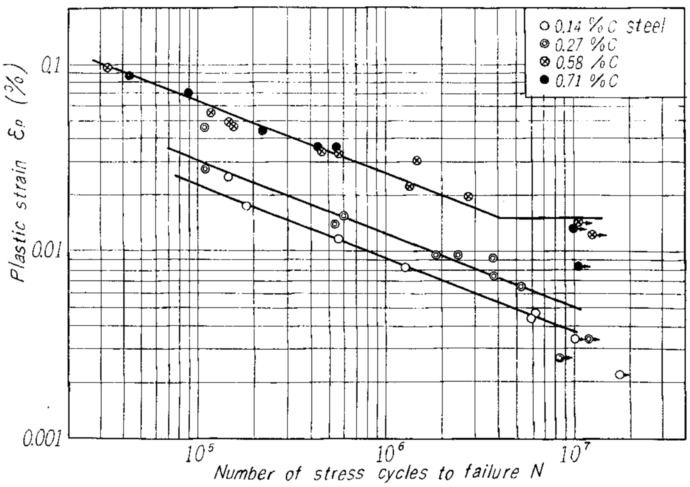

Fig. 7. Plastic strain vs. stress cycles to failure.

Fig. 7 shows a relation between ε_p and N on the log-log paper. It is clear that the relation is well represented by a straight line for each steel and these of 0.58% and 0.71% carbon steels, which belong to the high carbon steel, are given by the same line: and that at the same endurance life, a two or three times larger plastic strain occured in the high carbon steels than in the low carbon steels. These straight lines are expressed by the following formula,

$$\varepsilon_p \cdot N^{0.38} = K_1$$

where the exponent 0.38 is common for all four steels, and the constant K_1 is given in Table 3.

Fig. 8 indicates the relation of hysteresis energy w to N on the log-log paper. In this case, the relation is also represented by the straight line which is parallel to each other. It should be noted that the $w-N$ relation is generally different for different kinds of steel. And this fact seems to suggest that there is a difference in the storing capacity of energy in each steel, or there

Table 3. Endulance Limits and Constants K_1, K_2.

Materials	Endurance limit σ_w (kg/mm^2)	K_1	K_2
0.14% carbon steel	18.8	0.018	2.40
0.25% carbon steel	14.0	—	—
0.27% carbon steel	21.5	0.024	3.62
0.58% carbon steel	22.5	0.050	8.05
0.71% carbon steel	17.5	0.050	6.25

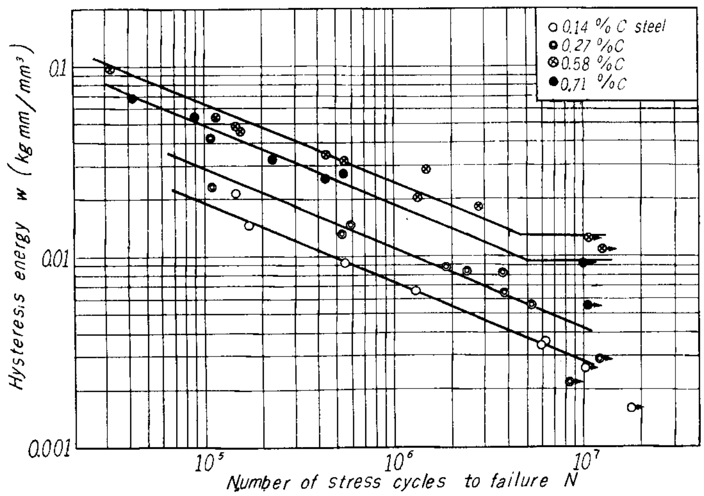

Fig. 8. Hysteresis energy vs. stress cycles to failure.

is a difference in its effect on the structure, and therefore, in its contribution for progress of fatigue for each steel. The straight lines in Fig. 8 are represented by the similar formula,

$$w \cdot N^{0.43} = K_2,$$

the values of K_2 which differ depending on the kind of steel are also given in Table 3.

Finally the stress-strain curve of each steel under completely reversed axial load is shown in Fig. 9, in which the amplitudes of stress and strain are taken to respective axis. The hollow circles in the figure represent the result of the short time test in which the stress amplitude was increased stepwise and the corresponding strain amplitude was measured. On the other hand, the solid circles are plotted based on the above mentioned strain measurements under fatigue stress, and then each circle gives the strain amplitude at 50% of total life at corresponding stress amplitude. For 0.25% carbon steel, only

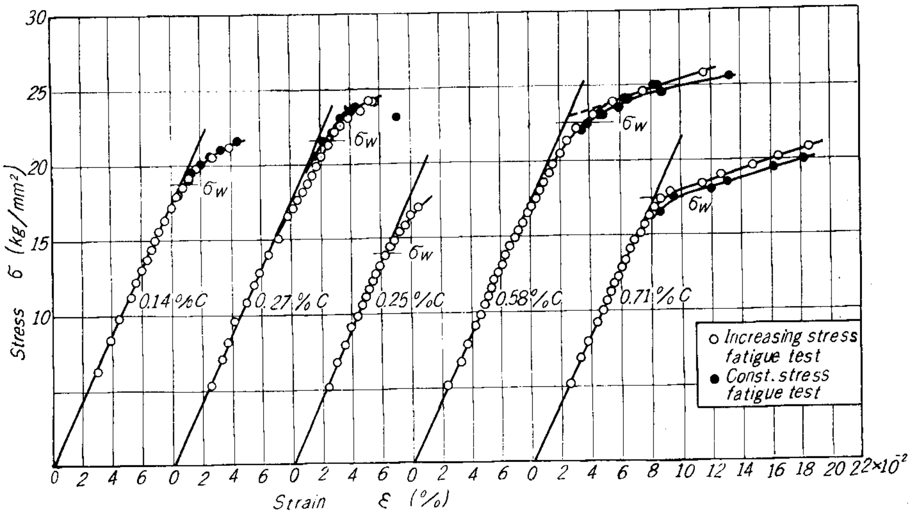

Fig. 9. Stress vs. strain.

the result of the short time test is plotted because of the above mentioned reason. σ_w in the figure gives the stress level of the endurance limit for each steel. It is clear that under repeating load the stress-strain relation of high carbon steels is well represented by straight line, and the intersect of this line passing the hollow circles to the elastic line gives the stress of the endurance limit with a good accuracy. Therefore, the endurance limit of materials, which reveal a relatively large plastic strain like the high carbon steels may be predicted from the stress-strain curve, obtained from the short time test under repeating load. However, such a method is not applicable for materials like the low carbon steels which reveal a less plastic strain under fatigue load.

4. Conclusions

The fatigue tests were carried out on five kinds of carbon steel under completely reversed axial load and the strain occuring in the specimen was measured using the previously developed fine measuring instrument. Discussions were made on the behaviour of the plastic strain under repeating load, the relations between plastic strain or hysteresis energy and the number of cycles to failure, and the nature of the stress-strain relations of each steel. Main conclusions are as follows.

The plastic strain occurring in the specimen during fatigue test shows a different behaviour depending on the carbon content of steel; the low carbon steels reveal a relatively larger variation of plastic strain in the initial stage in comparison with the high carbon steels, but the magnitude of the plastic strain itself is fairly less than that of the high carbon steels.

Only the 0.25% carbon steel, in spite of belonging to the low carbon steel, showed quite different behaviour of plastic strain, that is, the plastic strain was very small in the initial stage and then gradually increased through the complicated path such as a slight decrease followed after large but discontinuous increase. The further study seems to be needed to clearify the mechanism of that kind of particular phenomenon.

Excepting the 0.25% carbon steel, the relation between the plastic strain and the number of cycles to failure is well represented by a straight line for each steel on the log-log paper. Similar relation also holds when the hysteresis energy is taken instead of the plastic strain.

With respect to the stress-strain curve under fatigue load, there is also an apparent difference between the low carbon steels and the high carbon steels; the latter steels reveal a fairly large plastic strain when the stress is higher than the endurance limit, and in this stress range the stress-strain relation is represented approximately by another straight line differing from the elastic one. Furthermore, for materials whose stress-strain characteristics are similar to the above high carbon steels, the endurance limit may be determined from the stress-strain curve obtained from the short time test under repeating load.

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