Effects of Some Pre-cyclic Stressings on the Fatigue Strength Containing the Low Cycle Fatigue Range

By

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Abstract

It is already known that iron and many ferrous alloys show a characteristic coaxing or understressing effect.

In this report, some programmed fatigue tests were carried out to investigate the pre-stressing effect. Also, the micro Vickers hardness and macro residual stress of the specimen were examined. Experimental results are outlined, suggesting that the coaxing effect is due to the ability of steel to undergo strain hardening or strain aging especially at the crack tip area by strain cycling. It was found that only a small number of cycles of large overstressing can destroy the coaxing effects.

1. Introduction

Much research has been made about the effect of pre-stressing on the fatigue of materials. The phenomena known as coaxing or understressing effect are the results gained by such research.

A systematic investigation of such phenomena has been made by M. Kawamoto *et. al.*.[1] In their investigation, fatigue specimens were tested for many cycles at a stress below and also above the fatigue limit, and then tested to gain a S-N diagram. Results were as follows; the fatigue limit of prestressed specimen was the highest when the pre-stress coincided with the fatigue limit of the fresh specimen.

Another paper by J. C. Levy *et. al.*[2] also reports that coaxing is due to strain hardening and strain aging. Also, the scatter of fatigue strength may be responsible for coaxing.

Recently, a paper by S. Kitaoka *et. al.*[3),4] also reports that a decrease of the curva-

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ture at the tip of micro crack will cause coaxing.

From these works, it is evident that coaxing should not be attributed to just one reason but to several reasons combined.

In this paper, fatigue tests were carried out on S35C steel under programmed loading. Also, residual stress and micro Vickers hardness (Hv) were measured respectively on prestressed specimens in order to investigate the reason of coaxing. The effect of pre-strain by static tension was also examined. Through these tests, the characteristics of strain hardening by understressing were discussed.

2. Test Materials, Specimen and Test Equipments

2.1 Test Materials

S35C carbon steel was used. Its chemical compositions and its mechanical properties after heat treatment (730°C, 0.5 hr full annealed, cooled in the furnace) are listed in Tables 1 and 2.

Table 1. Chemical compositions (%)

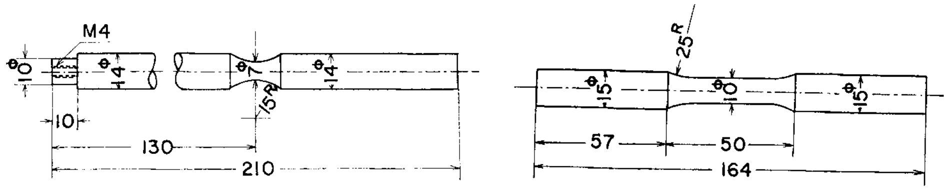
Mat.	C	Si	Mn	P	S
A	0.34	0.22	0.72	0.015	0.017
B	0.35	0.16	0.59	0.026	0.017

Table 2. Tensile properties.

Mechanical properties	A	B
Yield point (kg/mm^2)	31.8	32.1
Tensile strength (kg/mm^2)	53.2	55.4
Actual breaking point (kg/mm^2)	98.4	100.4
Elongation (%)	35.0	38.8
Reduction in area (%)	57.6	56.4

2.2 Test Specimen

Two types of test specimens were used and their shapes and sizes are shown in



(a) Cantilever type specimen (b) Ono type specimen

Fig. 1. Test specimen

Figs. 1.(a) and (b). The former is for the cantilever type and the latter is for the Ono type (constant moment type) of rotating bending fatigue test.

2.3 Test Equipments

A Cantilever type and Ono type of rotating bending fatigue testing machins were used. On the former type, two machines were used. One was run at high speed (2330 rpm) and the other at low speed (60 rpm). The Ono type machine was run at 2000 rpm.

For the measurement of residual stress, the Ono type test specimen was used. A wire strain gage was patched on the surface of the specimen, and after making a small hole at the axis of the specimen by drilling, the hole was enlarged by 10% nitric acid. The axial residual stress was computed by Sachs method.

Micro Vickers hardness in the cross section of the specimen was measured by an Akashi micro Vickers hardness testing machine (the weight being 200 gr.).

3. Test Precesure

Using the above devices, five kinds of fatigue tests were carried out, that is, (1) a fatigue test to gain an S-N diagram for fresh specimen, (2) a fatigue test to examine the effect of understressing, (3) a fatigue test to examine the effect of overstressing, (4) a fatigue test to examine the effect of overstressing on understressed specimen, and (5) a fatigue test to examine the effect of static tension strain. The load sequences of each test is shown in Table 3.

Micro Vickers hardness was measured on a fresh and pre-stressed specimen. Pre-stressing was σ_w-10^7 cycles, 1.2 σ_w-10^5 cycles and σ_w-1.6$\times10^7$ cycles→1.2 σ_w-10^5 cycles.

Residual stress was measured on a fresh specimen and σ_w-10^7 cycles pre-stressed specimen.

Table 3. Loading program.

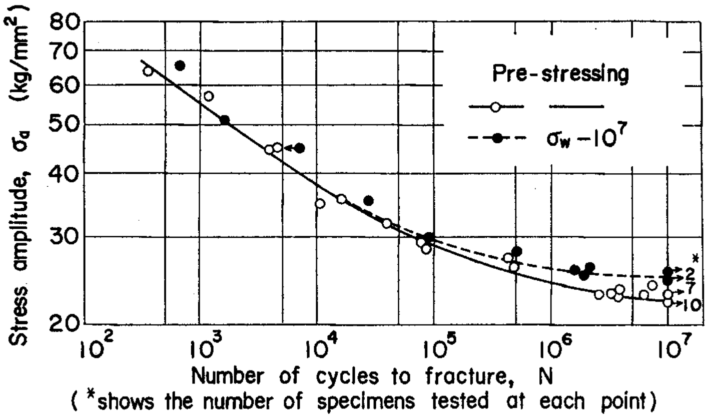
Case	Program
1	Fatigue test
2	σ_w–10^7 → Fatigue test
3	$2\sigma_w$–10^2 → Fatigue test
4	σ_w–10^7 → $2\sigma_w$–10^2 → Fatigue test
5	Tensile strain → Fatigue test

* σ_w: Fatigue limit

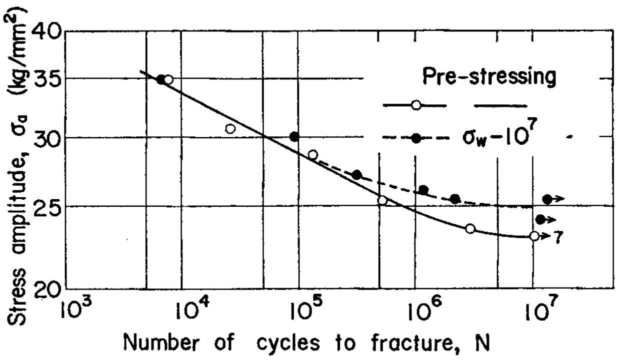
4. Test Results

4.1 Fatigue Test

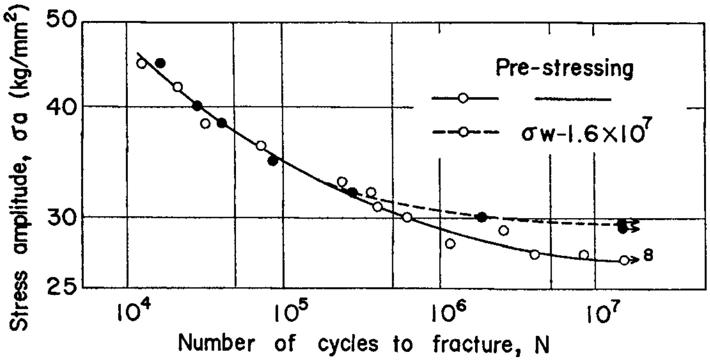
Fatigue test results of loading program (1) & (2) are shown in Figs. 2(a), (b) and



(a) Cantilever type, Material A



(b) Ono type, Material B



(c) Cantilever type, Material B

Fig. 2. Influence of understressing on fatigue strength (Loading program 1 & 2)

(c). The new fatigue limit after understressing is about 10% larger than the original fatigue limit.

Fatigue test results of loading program (3) and (4) are also shown in Fig. 3. Not only the fresh specimen but also the specimen which is strengthened by understressing have been weakened by overstressing. It is noteworthy that the fatigue strength is the same in both cases in spite of their differences of loading history.

Fig. 4 is the result of a fatigue test subjected to the loading program (5). Fatigue strength at 10^4 cycles is improved by tensile strain, but fatigue limit is not. And yet, with more tensile strain, both tend to be improved by the same rate.

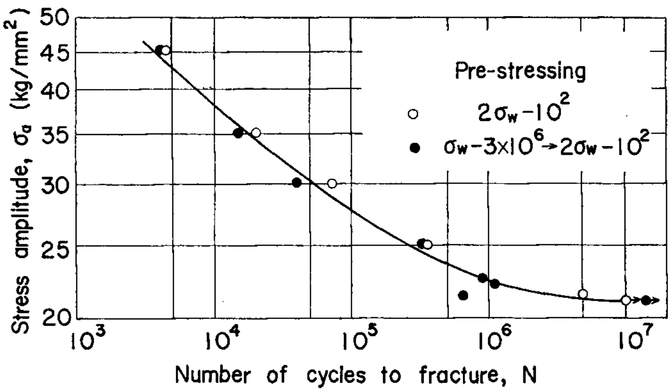


Fig. 3. Influence of overstressing on understressed specimen (Loading program 3 & 4, Cantilever type, Material A)

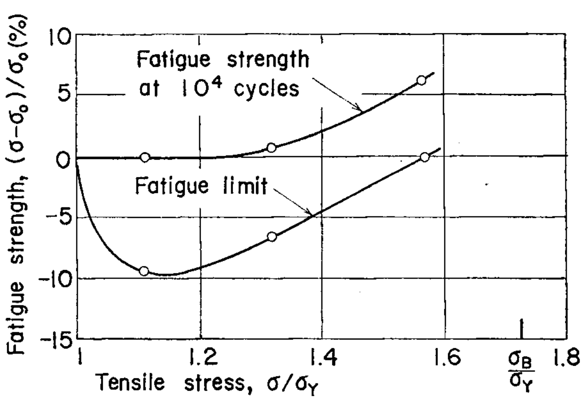


Fig. 4. Influence of pre-loading of tensile stress on fatigue strength (Cantilever type, Material B)

4.2 Micro Vickers Hardness

By understressing, micro Vickers hardness of the specimen is remarkably enlarged as shown in Fig. 5. However, no change is observed near the center of the specimen.

Assuming that a large plastic deformation had not occured in the specimen, the lower limit stress which produces the elevation of micro Vickers hardness was calculated, and the stress was 0.8 σ_w.

Further measurement of hardness was made on the specimen having the loading history as follows; 1.2 σ_w-10^5 and σ_w-$1.6\times10^7\rightarrow1.2\,\sigma_w$-$10^5$. The results are shown in Fig. 6. Micro Vickers hardness was linearly increased by the stress cycling below the fatigue limit, as shown in Fig. 5. However, the increment of the hardness by the stress cycling over the fatigue limit is not large; and it seems that the increment of the hardness has been saturated. The elevation of hardness by understressing is not attributed to the following increment of hardness by overstressing.

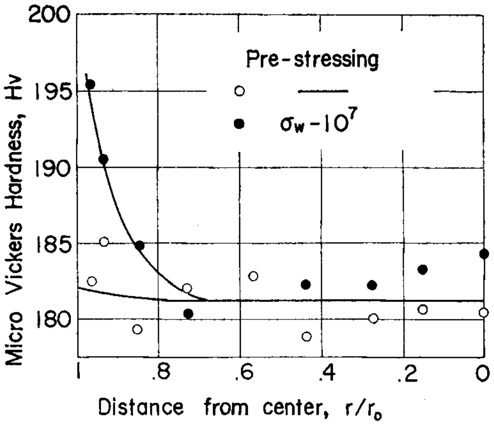


Fig. 5. Variation of micro Vickers hardness by understressing.

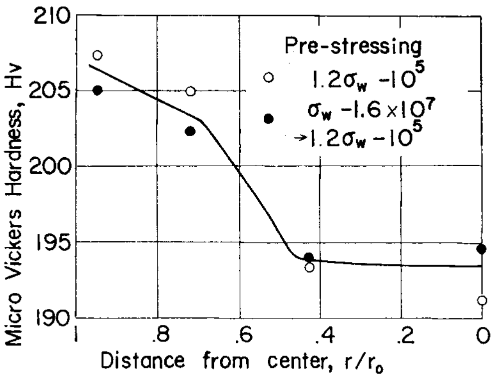


Fig. 6. Micro Vickers hardness by pre-stressing of understress and overstress.

4.3 Residual Stress

Residual stresses on fresh and understressed specimens are shown in Fig. 7. Here, instead of a residual stress the axial strain change is shown when the hole, drilled at the axis of the specimen, is enlarged by etching. Little difference of residual stress is observed on fresh and understressed specimens.

5. Discussion of Results

It is obvious that the macro residual stress never contributed to the coaxing, as shown in Fig. 7. Consequently, the coaxing should be attributed to the micro change in materials.

The lower limit stress which produced an increment of micro Vickers hardness is about 0.8 σ_w as estimated from Fig. 5. This fact agrees with the results observed by S. Kitaoka *et. al.*[5] on rotating bending and torsional fatigue tests. Micro Vickers hardness seems to increase linearly with the increase of stress amplitude within the range of 0.8 σ_w to σ_w. However, the rate of increase of micro Vickers hardness becomes smaller if the stress amplitude is larger than σ_w, as is shown in Fig. 6. No influence is observed on the increase of micro Vickers hardness by overstressing (1.2 σ_w-10^5 cycles). Considering that the increase of micro Vickers hardness depends on stress amplitude, this increase should be regarded as strain hardening. From these facts, the rate of strain hardening by stress cycling seems to be saturated, and its saturation value depends on stress amplitude.

By overstressing, the fatigue limit drops slightly (Fig. 3). The specimen understressed shows the same fatigue limit and S-N diagram by a small number of cycles of large overstressing. Namely, a small number of cycles of large overstressing destroys the understressing effect. As it is quite normal that stress cycling accompanies strain hardening, coaxing cannot be attributed to a simple strain hardening, but to some conditional strain hardening.

In the case of the pre-strained specimen, fatigue strength at 10^4 cycles is improved, as shown in Fig. 4; and that should be attributed to the effect of strain hardening. However, the fatigue limit drops. That is, strain hardening in this case influences not only the fatigue limit but also the fatigue strength. On this point, this case differs

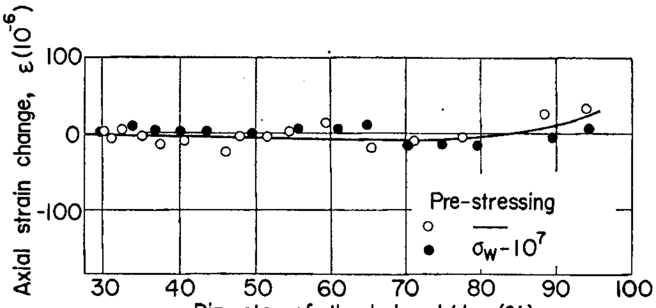


Fig. 7. Residual stress by understressing.

remarkably from the case of understressing. Since the fatigue limit is not improved, the micro crack produced by tensile strain should be considered.

In fact, M. Kawamoto *et. al.*[6] have already pointed out that a rolling precedure, not harmful to micro crack, improved the fatigue limit 20–30% at its maximum.

However, it should be rememembered that the rate of work hardening by rolling is much larger than by understressing; and an effective compressive residual stress may be produced by rolling.

Before any further discussion, we should realize that the existence of a fatigue limit is a special phenomenon. There is general agreement that, for metals, there exist two kinds of S-N diagrams in the shape. Fatigue limit is a term appropriate for those materials which either fail in a few million cycles, or never fail at all. Furthermore, it has been found that fatigue limit is peculiar to steels (chiefly low-carbon steels tested in a non-corrosive environment). Recently, it was found that coaxing is also peculiar to those materials.

The paper by T. Tanaka *et. al.*[7] reports that steel shows an unelastic behaviour even if the cycling stress level is equal to the fatigue limit. It is doubtful that this unelastic behaviour is based only on the plasticity of material. However, from the fact that an increase of hardness is observed by understressing, it is natural that a plastic deformation be also cycled. Further research is necessary to explain the reason why a specimen never fails in spite of the cycling of the plastic strain.

Here, assuming the existence of a fatigue limit, further discussion is possible. From the above results, many phenomena are observed that indicate coaxing is not explained by a uniform work hardening of material; i.e.,

(a) The effect of understressing is observed only on the fatigue limit.

(b) The rate of work hardening by understressing is relatively small.

(c) The increase of the fatigue limit by understressing is about 10%; and by rolling, the increase is at most 20–30% in spite of a great difference in the rate of work hardening.

(d) Work hardening by tensile strain improves fatigue strength mainly at low cycles.

From the report by M. Kawamoto, *et. al.,*[1] pre-stress level is also important.

All these facts indicate that coaxing occurs by a remarkable strain hardening at the local region, possibly at the tip of the micro cracks. That the rate of coaxing depends mainly on the stress level cycled, and that an increase of the number of cycles contributeless, seems to indicate that coaxing depends on strain hardening. However, it is also reported that coaxing depends on strain aging[5]. Therefore, further investigation is needed to decide if coaxing depends only on strain hardening.

6. Conclusion

The effect of pre-cyclic stressing is investigated on S35C carbon steel. The results are as follows;

(1) The increase of the fatigue limit by understressing was about 10%, and an increase of micro Vickers hardness was observed. The fatigue strength was not changed, only a fatigue limit.

(2) By understressing, macro residual stress did not occur.

(3) The effect of understressing on the fatigue limit and micro Vickers hardness was destroyed by a small number of cycles of large overstressing.

(4) The increase of the fatigue strength at low cycles was observed by pre-strain, but the fatigue limit was lowered.

(5) From the above facts, the coaxing effect should be attributed to the strengthening of the material at an easy glide area, especially at the tip of micro cracks.

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