EFFECTS OF SLAG INCLUSIONS IN CARBON STEELS ON THEIR FATIGUE STRENGTH

Ishibashi, Tadashi
Research Institute for Applied Mechanics, Kyushu University

Uryu, Tsunemi
Research Institute for Applied Mechanics, Kyushu University

https://doi.org/10.5109/7156979

出版情報：Reports of Research Institute for Applied Mechanics. 1 (3), pp.107-115, 1952-07. 九州大学応用力学研究所
バージョン：
権利関係：

Reports of Research Institute for Applied Mechanics
Vol. I, No. 3, July, 1952

EFFECTS OF SLAG INCLUSIONS IN CARBON STEELS ON THEIR FATIGUE STRENGTH*

By Tadasi ISIBASI, Tsunemi URYU

To see the effect of post-annealing on the fatigue strength of carbon steel plain specimens rotary bending tests were made. It has been found that fatigue limits of post-annealed specimens decrease considerably as compared with those of specimens without such annealing. As to the cause of such detrimental effects of post-annealing notch-effects of hair cracks which would start from slag inclusions in steels were mentioned. In order to estimate the size of the hair cracks fatigue strength of specimens with a shallow round crack was measured.

1. Introduction. In a former paper[1] we have reported that the fatigue strength of a notched carbon steel specimen decreases considerably, if the specimen is annealed at a temperature above the allotropic point of the material after the final surface finish of the specimen, as compared with that of a specimen without such annealing. It was found, moreover, that the decrease was remarkable when the notch was sharp.

About this fact it was shown that such a difference in fatigue strength between specimens annealed and not annealed was due to absence or presence of thin strain-hardened layer existing at the root of the notch as a result of the action of bit in the cause of machining the notch.

In the case of plain specimens in which stress distribution is nearly even it will be expected that the difference in fatigue strength between specimens annealed and not annealed will be very small. However, contrary to this expectation, decrease of fatigue limits of plain specimens of carbon steels due to post-annealing — annealing after the final surface finish of the specimens — is also observable when there are many slag inclusions in the steels.

This report concerns with a study of this fact and explains that such decrease of fatigue limits is due to the notch-effects caused by hair cracks started from slag inclusions in steels. Under slag inclusions we understand not only such large inclusions as so-called ghost lines but also such small ones as sulphides, oxides or silicates which are scattering at random in the materials.

* Read before the First Japan National Congress for Theoretical and Applied Mechanics (Tokyo), November 3, 1951.

1) T. Isibasi, T. Uryu, "On the condition of occurrence of fatigue failure in sharply notched specimens" Rep. Res. Inst. Elas. Engg., Kyushu Univ., 7, 1950, 1.

In order to confirm the notch-effects of such hair cracks, rotary bending tests were performed with plain specimens of various carbon steels as well as with specimens with a shallow round crack.

2. Experiments with plain specimens. In order to examine the decrease of fatigue limits of plain specimens due to post-annealing, carbon steels of various carbon contents ranging from 0.12% to 0.79% carbon were used. Their chemical composition and mechanical properties are shown in Table 1.

TABLE 1. Chemical composition and mechanical properties of the steels used (Annealed state).

Steel	Annealing temp., °C	Chemical composition, %					Mechanical properties, kg/mm², %				
		C	Mn	Si	P	S	σ_{Su}	σ_{Sl}	σ_B	σ_T	φ
0.12% C steel	900	0.12	0.38	0.12	0.02	0.03	30.8	26.0	39.7	86.4	33.8*
0.16% C 〃	890	0.16	0.82	0.14	0.02	0.03	31.9	28.5	46.7	89.7	36.4
0.18% C 〃	880	0.18	0.41	0.24	0.03	0.03	25.5	23.1	38.7	81.3	33.0
0.22% C 〃	880	0.22	0.51	0.08	0.03	0.02	29.8	27.2	43.7	87.2	30.0
0.33% C 〃	830	0.33	0.86	0.13	0.02	0.03	32.2	27.8	55.7	108.7	35.4
0.53% C 〃	790	0.53	0.48	0.13	0.07	0.03	33.2	29.8	61.4	85.6	22.0
0.63% C 〃	750	0.63	0.62	0.14	0.02	0.02	29.5	—	62.2	96.5	19.0
0.79% C 〃	750	0.79	0.40	0.35	0.06	0.03	35.6	32.8	68.4	122.6	26.6

σ_{Su}; upper yield point, σ_{Sl}; lower yield point, σ_B; tensile strength, σ_T; actual stress at fracture, φ; elongation (gauge length 50 mm),
* gauge length 100 mm.

All specimens (12 mm dia.) were turned from round bars of about 20 mm dia. Before turning all bars were annealed at the temperature above their allotropic point for 30 min. followed by cooling in the furnace. After rough cutting the specimens were grouped in two series. Specimens in one series, say Series A, were annealed again after rough cutting at the same temperature as that of the initial annealing. After this second annealing they were turned and finished the surfaces with 0000 emery paper and used as test-specimens. Specimens in another series, say Series B, were turned without the second annealing and finished the surfaces with 0000 emery paper. But after the final finish of the surfaces all specimens in Series B were annealed at the same temperature as that of the initial held in a tight steel box packed closely with steel cutting chips in order to prevent excessive oxidation of the surfaces. Thereby, in practice, the oxidation films on the surfaces of the specimens were only some 0.002 mm in thickness and would not probably influence on the test results.

Fatigue limits of the specimens of these two series were so determined that an increase of stress by $0.25 \sim 0.5$ kg/mm² above the fatigue limits caused the specimens broke down before 10^7 repetitions of stress were reached. The speed of stress repetitions was about $2500 \sim 2700$ r.p.m., The fatigue limits are shown in the third and in the fourth column of Table 2. In the second column of the same table the annealing temperature of each steel is given.

TABLE 2. Results of fatigue tests (Plain specimen).

Steel	Annealing temp., °C	Fatigue limit, kg/mm²		Depth of decarburized layer, mm	B/A
		Series A, (As made)	Series B, (Annealed)		
0.16% C steel	890	25.75	22.25	0.05	0.86
0.18% C 〃	880	23.5	20.5	0.00	0.87
0.22% C 〃	880	25.0	20.25	0.04	0.81
0.33% C 〃	830	25.25	20.5	0.00	0.81
0.53% C 〃	790	26.75	21.75	0.02	0.81
0.63% C 〃	750	25.0	24.5	0.00	0.98
0.79% C 〃	750	30.0	25.25	0.00	0.84
0.12% C steel	900	23.0	20.5	0.15	0.89
〃	750	—	20.5	0.05	0.89
〃	700	—	20.5	0.00	0.89
〃	650	—	21.0	0.00	0.91
〃	600	—	23.5	0.00	1.02

From this table we see that the decrease of the fatigue limits of specimens in Series B as compared with those of specimens in Series A is nearly indifferent to the carbon contents. It is probable to consider that the fatigue strength of the specimens in Series B may be reduced by some extent due to the decarburized layers near the surfaces of the specimens in spite of the care taken not to decarburize in the course of the post-annealing after the specimens were finished. So the thickness of the decarburized layers was measured from microphotograph of the cross section of each specimen, and it was found (Table 2) that the thickness of these decarburized layers, if exist, was so thin that the considerable decrease of fatigue strength of specimens in Series B could not be explained by the existence of such layers.

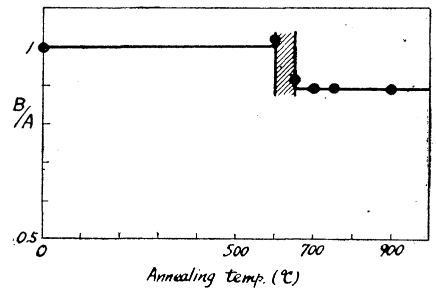


FIG. 1. Relation between B/A and annealing temperature (0.12 %C steel).

In order to see the effect of the annealing temperature on the ratio B/A, tests were made with 0.12 % C steel. The results are shown in Table 2 and in Fig. 1.

As seen in Fig. 1 the values B/A do not decrease up to the temperature of about 600° C., but they decrease abruptly at 650° ~ 700° C. and become constant remaining unchanged above these temperatures. The decarburized layers were also measured in this case; the layers couldn't be seen in the specimens annealed up to 700° C., but thin layers were visible in the specimens annealed at higher temperatures. This fact leads us to decide again that the decarburized layers at the surfaces of the specimens can not be the cause of the decrease of the fatigue strength.

Before going to further discussions about these results some remarks on the microphotographs of the materials (Fig. 2) must be made. All the materials used were examined with microscope and it was found that many small slag inclusions were visible scattering all over the materials. Fig. 3 is an example showing some inclusions in 0.12 % C steel; the largest inclusion is about 0.05 mm in size.

It is probable to consider that those inclusions will act as stress raisers and fatigue cracks will start therefrom[2)], since it has been sometimes reported[3)] that hair cracks appear on the surfaces of machined steel bars starting from slag inclusions.

Another example showing the reduction of the fatigue strength of plain specimens by the post-annealing after the final surface finish of the specimens can be seen in the H. F. Moore's report[4)]: In his experiments the fatigue limit of S.A.E. 1035 steel* specimens (6.35 mm dia.), machined and polished after they were annealed in vacuo at 816° C. for 2 hr. and then slowly cooled still under vacuum but not annealed after the final finish of surfaces of the specimens, was 27.4 kg/mm², whereas the fatigue limit of specimens in other series, which were machined and polished and then bright annealed as before, reduced to 23.9 kg/mm². It was, furthermore, observed that the polished surfaces of the specimens remained bright after the vacuum-annealing and the microphotographs of the specimens annealed showed no evidences of surface decarburization. The value of B/A in this case is, therefore, 0.87 showing the same order of reduction of fatigue strength as we observed in our experiments.

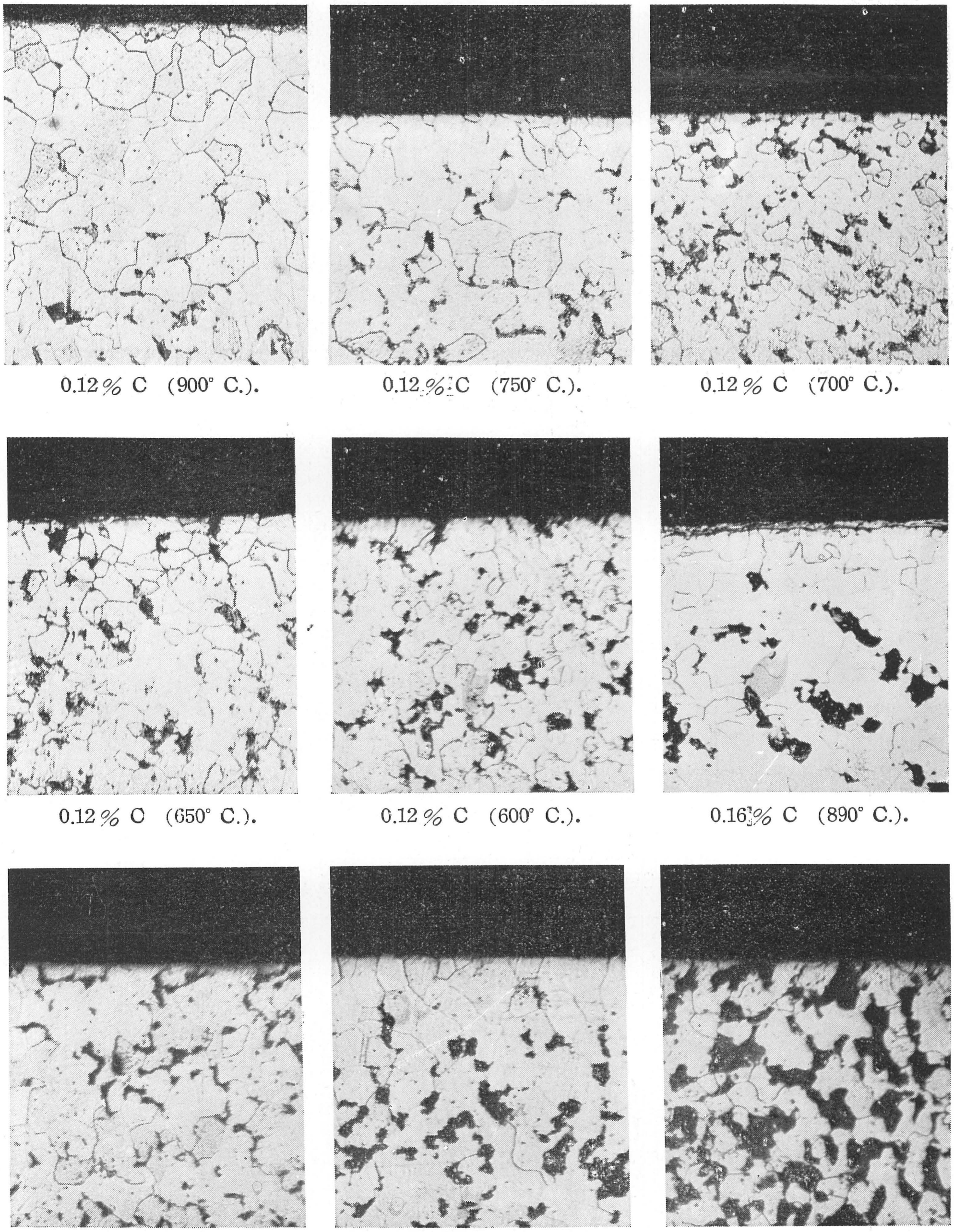
3. Experiments with round-cracked specimens. In order to estimate the notch-effect of a hair crack in the material the crack strength of round-cracked specimens was measured. To have round-cracked specimens sharply round-notched bars of 0.12 % C steel, annealed at 900° C. for 30 min. before turning, were prepared; the round-notch was 60° V-groove and 1 mm in depth, the radius of the notch was about 0.05 mm and the

2) H. F. Moore, J. B. Kommers, "The fatigue of metals" 1927, p. 195.

3) S. Ammareller, "Seigerungen und Festigkeitseigenschaften eines Schwiedestückes aus einem 56-t-Block", Stahl u. Eisen, 70, 1950, 4, p. 131.

4) H. F. Moore, "A study of size effect and notch sensitivity in fatigue tests of steel", Proc. Am. Soc. Test. Mat., 45, 1945, p. 507.

* S.A.E. 1035 steel: C = 0.34 %, Mn = 0.78 %, Si = 0.24 %, S = 0.03 %, P = 0.02 %; $\sigma_S = 30.5$ kg/mm², $\sigma_B = 54.6$ kg/mm², $\varphi = 27.5$ %.

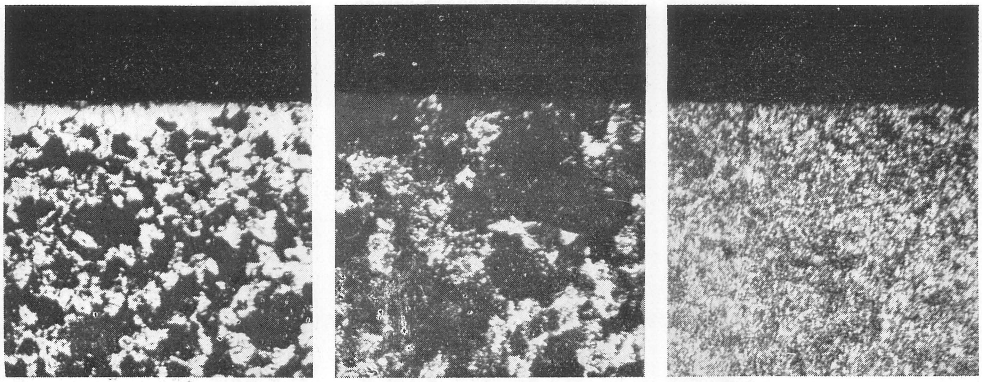


0.12 % C (900° C.). 0.12 % C (750° C.). 0.12 % C (700° C.).

0.12 % C (650° C.). 0.12 % C (600° C.). 0.16 % C (890° C.).

0.18 % C (880° C.). 0.22 % C (880° C.). 0.33 % C (830° C.).

FIG. 2. Microphotographs of the steels used (× 150) .
Cross section of each specimen. Temperature in parenthesis shows the annealing temperature.



0.53 % C (790° C.). 0.63 % C (750° C.). 0.79 % C (750° C.).

FIG. 2. *(begins on page* 111)

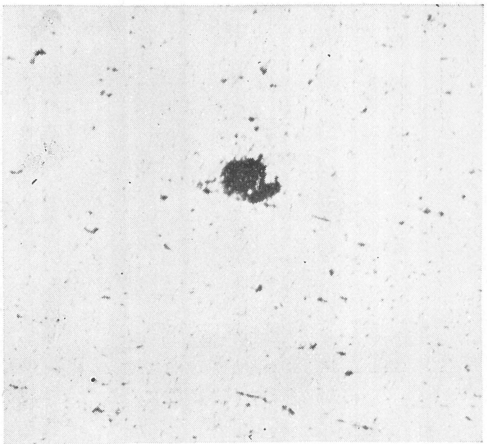


FIG. 3. Slag inclusions in 0.12 % C steel ($\times$ 150).

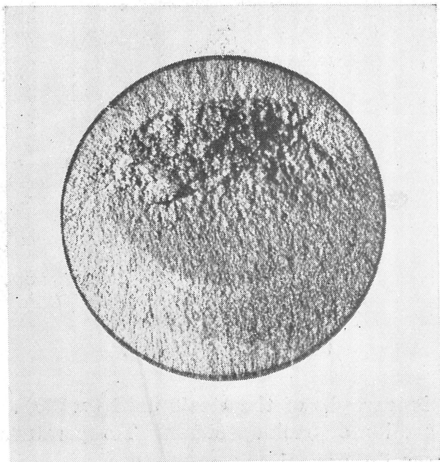


FIG. 5. Fractured surface of a cracked specimen (No. 8, $\times$ 3).

minimum section at the root of the notch was 14 mm in diameter. These notched specimens were subjected to rotary bending stress higher than their fatigue limit for proper number of stress repetitions in order to form the round fatigue crack at the root of the notch, the depth of which depends on the number of stress repetitions even if the load on the specimens is maintained constant. In the present case, stress of 14 kg/mm^2 (the nominal stress reckoned on the minimum section) and stress repetitions of 4×10^5 were enough to have a wanted depth of crack (about 0.25 mm). After the crack was formed the mechanical round-notch of the specimens was turned off and we had round-cracked specimens, i.e. plain specimens (14 mm dia.) with a round crack.

The cracked specimens thus made were grouped in two series as before: Specimens in Series A were heated in a furnace at 300° C. for 30 min. in order to colour the cracked part so that after the specimens were broken we could measure the depth of crack by measuring the coloured part on the fractured surfaces, whereas specimens in Series B were annealed at 700° C. for 30 min. followed by cooling in the furnace in order to relieve the specimens of the strain-hardened region at the end of the crack, since severely strain-hardened layer must be existed there due to cracking. The depth of the initial crack in specimens of this series was also measured from the length of the coloured part — due to stress relief heating at 700 °C.— on the fractured surfaces.

The results of fatigue tests are shown in Table 3 and in Fig. 4, in which the stresses are the nominal stresses reckoned on the minimum sections.

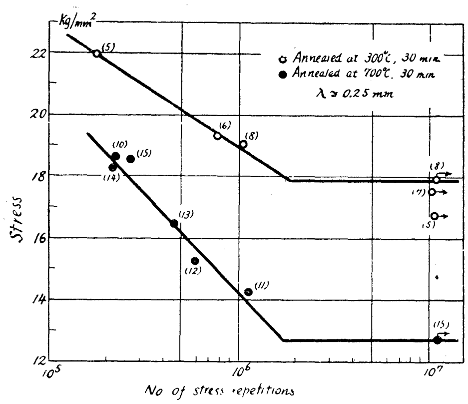


FIG. 4. S-N curves of round-cracked specimens (0.12 % C steel). Arrows show specimens not broken. Numbers in parentheses are specimen No.

TABLE 3. Results of fatigue tests of round-cracked specimens (0.12 % C steel).

Fatigue limit, kg/mm^2		Annealing temp., °C	Depth of crack, λ, mm	B/A
Series A	Series B			
17.9	12.7	700	0.25	0.71

Fig. 5 shows a fractured surface of cracked specimen, in which the outer dark region is the initially cracked part coloured by the heating explained above.

4. Discussion of results and conclusions. About the cause of the decrease of fatigue limit of post-annealed specimens (Series B) mentioned above, the notch-effects of inclusions themselves will seemingly be considered to be responsible. But this is not the case. For, since slag inclusions are existing scattered in the material, there are many cases in which fatigue crack in the specimens in Series A will start from the inclusions existing just below the thin strain-hardened layer, which must naturally be present near the surface of the specimen due to machining, irrespective of the fact that the stress on the surface is maximum since such layer has a higher fatigue resistance than the material in virgin state. On the other hand, if the specimen is annealed after final finishing, the thin strain-hardened layer will disappear returning the surface to the annealed state and consequently fatigue crack will start from the inclusions on the very surface. But the decrease of the fatigue limit of annealed specimens (Series B) will be very small as compared with that of not annealed specimens (Series A) since such decrease is proportional to the thickness of the strain-hardened layer.

To explain the considerable decrease of fatigue limit of annealed specimens as observed in the experiments, therefore, some larger notch-effects than those of slag inclusions themselves must be expected in the strain-hardened layer near the surfaces of the specimens. It is natural to think that some hair cracks will start from the inclusions on the surfaces of the specimens due to machining and the notch-effects of these hair cracks will cause the lowering of the fatigue limit of specimens in Series B. When the surface of a specimen with hair cracks on its surface is hardened by plastic deformation (due to machining, for example) the notch-effects of these hair cracks will be cancelled by the rise of fatigue strength of the deformed zone and the fatigue limit of the hair-cracked specimen not annealed, therefore, will decrease only little or not at all. But if a hair-cracked specimen is annealed it will be relieved of the strain-hardened layer and the notch-effects of hair cracks will appear causing the decrease of the fatigue strength of the specimen.

The softening of the hardened region must take place at such a temperature as a recrystallization temperature, so the effect of annealing on the lowering of the fatigue strength will begin to appear at the annealing temperature of about 650° C., at which recrystallization of the grain of the steel will begin and the hardened layer will be softened. Fig. 1 shows this fact clearly.

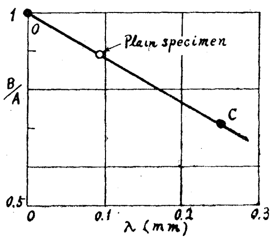


FIG. 6. Relation between B/A and depth of crack, λ, (0.12 % C steel).

To have a rough idea about the magnitude of hair cracks supposed to be present near the surface started from the slag inclusions Fig. 6 is useful. In Fig. 6 the value of B/A of round-cracked specimen is plotted (point C). The depth of the crack was about 0.25 mm. If hair cracks are absent, that is when $\lambda = 0$, B/A is supposed to be equal to unity. Assuming, momentarily, that B/A will decrease linearly with λ, the straight line OC will be obtained showing the relation between B/A and depth of round crack. Comparing the value of B/A of plain specimen with that of round-cracked one (line OC), the equivalent dimension of the hair cracks supposed to be present near the slag inclusions can be estimated to be about 0.09 mm. Though these hair cracks will not be round in their forms the value of 0.09 mm seems to be reasonable at least in its order of magnitude.

Thus the following conclusions were obtained:

1) The fatigue limits of carbon steel plain specimens post-annealed after their final surface finish decreased by $10 \sim 20$ per cent of those of specimens without such annealing.

2) This decrease in fatigue strength was reasonably explained by considering the notch-effects caused by hair cracks started, during machining, from the slag inclusions near the surfaces of the specimens.

3) The dimension of these hair cracks was estimated to be the same order of magnitude as the linear dimension of the slag inclusions in steels.

(Received April 22, 1952)