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https://doi.org/10.5109/7156995

出版情報：Reports of Research Institute for Applied Mechanics. 2 (6), pp.65-74, 1953-06. 九州大学応用力学研究所
バージョン：
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Reports of Research Institute for Applied Mechanics
Vol. II, No. 6 June, 1953.

FATIGUE STRENGTH OF CARBON STEEL BARS WITH ROUND-CRACK*

By Tadasi ISIBASI, Tsunemi URYU

Notch-effects of minute cracks in carbon steel bars of various carbon contents with a round-crack were measured under rotary bending stress. The detrimental effects of post-annealing (annealing after the original crack was made) on fatigue strength of cracked specimens were studied. The notch-factor β_c of a crack seems to be indifferent to carbon content in steel and is about $1.3 \sim 1.5$, so far as the depth of crack is shallow ($0.25 \sim 0.5$ mm, dia. of specimens 14 mm). β_c increases, however, to $1.7 \sim 1.9$ when the specimens are post-annealed. For both specimens, post-annealed and not post-annealed, β_c increases as the depth of crack deepens.

1. Introduction. Recent development of method of crack detection makes it possible to disclose minute cracks in machine parts or structural members, which escaped our notice so far. We are, some times, entailed to know the strength of such cracked members especially under repeated load in order to determine the usefulness of such members.

We measured, therefore, the strength of carbon steel bars with a round-crack (called as round-cracked specimens in the following) under repeated load (rotary bending). The effects of post-annealing (annealing after original round-crack was made) on the fatigue strength of such bars were also measured. The strength of the round-cracked specimens is expressed in terms of the notch-factor β_c (ratio of fatigue limit of plain specimens to that of cracked ones) by considering that the crack is the sharpest of all possible notches. Since the predominant dimension of a crack as a notch is its depth, β_c was considered to be a function of the depth of crack.

2, Materials used and preparations of ronnd-cracked specimens. The materials used were carbon steels of the following composition and properties (Table 1). Their microphotographs are shown in Fig. 1.

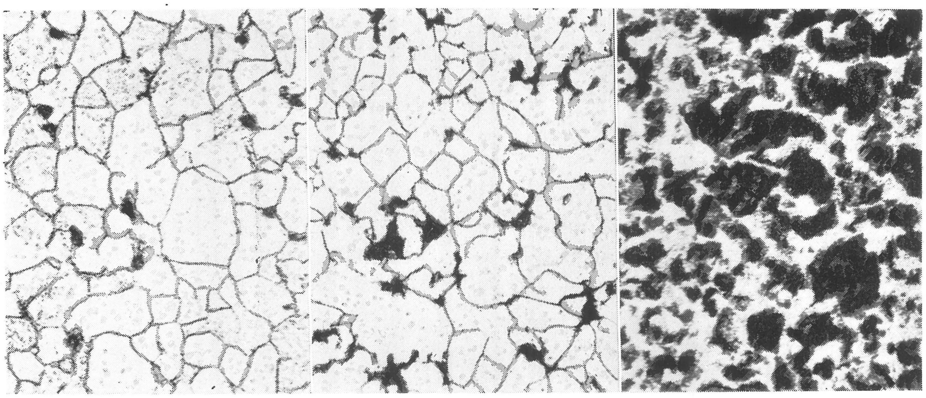
In order to make round-cracked specimens, a sharp circumferential 60° V-groove with notch radius of about 0.05 mm was machined in the specimens which were turned from round bars of about 20 mm dia. These bars were annealed, before turning, at the temperatures shown in Table 1 for 30 min. followed by cooling in the furnace. The depth of the machined notch was 1 or 1.5 mm and the minimum section at the root of the notch was 14 or 16 mm in dia. (see the fourth column of Table 2). These notched

* Read before the 29th General Meeting (Tokyo) of Japan Soc. Mech. Engs., April 2, 1952.

TABLE 1. Chemical composition and mechanical properties of the materials 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
0.08 % C steel	900	0.08	0.31	0.01	0.01	0.03	23.4	20.0	31.5	77.2	45.0
0.12 % C steel	〃	0.12	0.38	0.12	0.02	〃	30.8	26.0	39.7	86.4	33.0*
0.53 % C steel	790	0.53	0.48	0.13	0.07	〃	33.2	29.8	61.4	85.6	22.0

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.



0.08 % C steel. 0.12 % C steel. 0.53 % C steel.

Fig. 1. Microphotographs of the steels used (× 150).

specimens were subjected to uniform rotary bending stress, a little higher than their fatigue limits, for some numbers of stress repetitions in order to make a circumferential fatigue crack at the root of the machined notch. The depth of the developed crack depends on the numbers of stress repetitions. To foresee the depth of the crack without breaking the specimens machine was stopped many times in the course of stress repetitions and the deflection due to statical bending moment of the middle point of each specimen was measured with a Zeiss's dial indicator. And from the magnitude of deflection the depth of the crack was estimated. After a crack of wanted depth was developed the machined notch of the specimens was turned off having the round-cracked specimens.

To see the effects of post-annealing on the fatigue strength of round-cracked specimens the specimens were grouped in two series. Specimens in one series were heated at 300°C. for 30 min. in a furnace in order to colour the cracked part so that after the specimens were broken we could determined the depth of the original crack by measuring the coloured part on the fractured surfaces. While specimens in another series were annealed at 700°C. for 30 min., held in a steel box tightly packed with steel cutting chips in order to prevent excessive oxidation of the surfaces, 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 original crack in specimens in this series was also measured from the length of the coloured part — coloured due to the annealing — on the fractured surfaces.

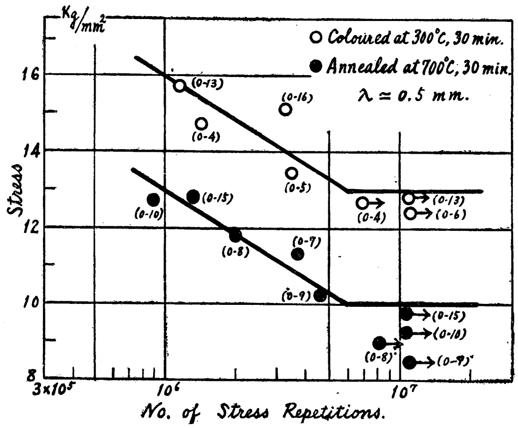


Fig. 2. S-N curves of round-cracked specimens (0.08% C steel).

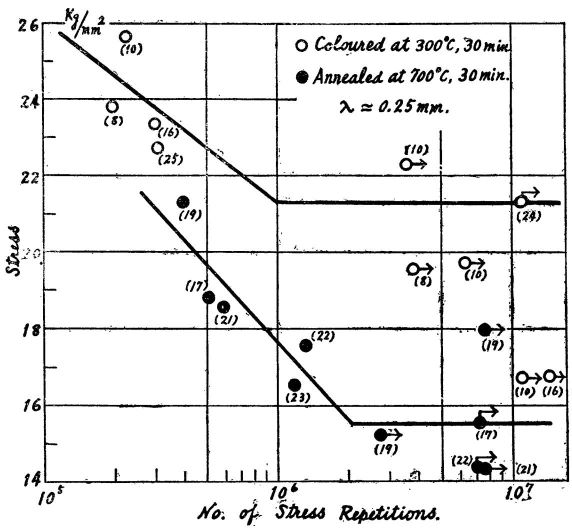


Fig. 3. (a).

3. Experimental results. The S-N curves obtained are shown in Figs. 2 and 3-a) ~ d). (The fatigue data of 0.12% C carbon steel specimens with round-crack of about 0.25 mm depth have been reported elsewhere[1]). In these Figs. arrows show specimens not broken and numbers in parentheses

Fig. 3. (a), (b). (c), (d), S-N curves of round-cracked specimens (0.53% C steel).

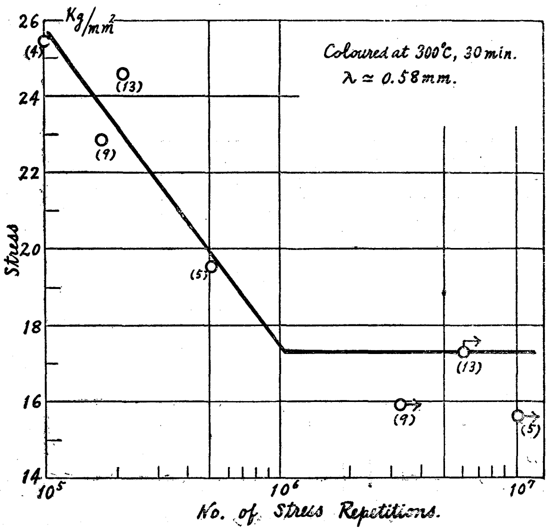


Fig. 3. (b).

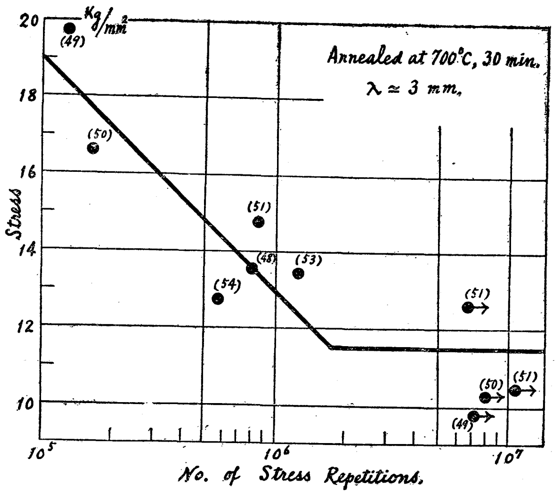


Fig. 3. (c).

[1] T. Isibasi, T. Uryu, "Effects of slag inclusions in carbon steels on their fatigue strength", Rep. Res. Inst. App. Mech., Kyushu Univ., 1, 1952, p. 107.

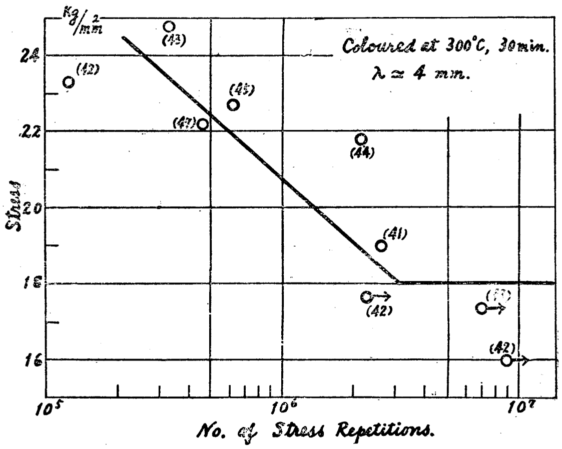


Fig. 3. (d).

are specimen No. In some cases specimens endured over 10^7 of stress repetitions were subjected to higher stress level than before so that we were able to measure the depth of the original crack by breaking the specimens without deformation. The stresses are the nominal ones reckoned on the actual residual section reduced by the cracked part, of which the magnitude was measured after the specimens were broken. Refering to Fig. 4, which is a shematic representation of the broken section, when the depth of the original crack (region A) was not uniform along the circumference of the section, the distance QP was regarded as the depth of the original crack λ since the crack advanced the battered region B due to stress repetitions was observed to start near the point P by inspecting the appearances of the fractured surface. The nominal stress of the specimen was therefore regarded as the stress of the point P by taking the section modulus of the region B (nearly elliptical form) about x-axis. The original cracked part of the section was regarded not to carry anything of stresses so long as the length λ was smaller than 1 mm. However when λ was 3 or 4 mm, calculation

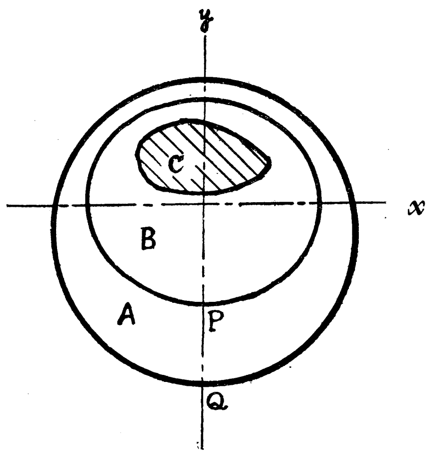


Fig. 4.
Fractured surface (Shematic).
A; Original round-cracked region.
B; Battered region.
C; Final fractured region.

of the nominal stress at the point P was made by assuming, after R. E. Peterson[2], that the cracked part will support compressive stress but not tensile one while the stress distribution is linear as usual. Some photographs of the fractured surfaces are shown in Plate 1 and 2 at the end of the paper.

The numerical results are shown in Table 2 and in Fig. 5. In Fig. 5 the notch-factors β_c of the round-cracked specimens are seen to be indifferent to carbon contents in steels though β_c increases as the depth of the crack deepens. This latter fact that β_c increases as the depth of crack means that, if a cracked specimen is subjected to stress great enough to start a new crack at the end of the original one, the new crack will develop ensuing breakdown of the specimen.

TABLE 2. Results of fatigue tests on round-cracked specimens of carbon steels.

Steel	Plain specimen		Round-cracked specimen						
	Dia., mm	Fatigue limit, kg/mm²	Dia., mm	Depth of crack, λ, mm	Fatigue limit, kg/mm²: Not annealed*	Fatigue limit, kg/mm²: Annealed**	Notch-factor, β_c: Not annealed	Notch-factor, β_c: Annealed	Cracking stress+, kg/mm²
0.08% C steel	12	19.25	14	0.5	13.0	10.0	1.48	1.93	15.0
0.12% C steel	〃	23.0	〃	0.25	17.9	12.7	1.28	1.81	〃
0.53% C steel	〃	26.75	〃	〃	21.3	15.5	1.26	1.73	18.0
			〃	0.58	17.3	—	1.55	—	〃
			16	3	—	11.5	—	2.33	17.5
			〃	4	18.0	—	1.49	—	〃

* Coloured at 300° C. for 30 min.
** Annealed at 700° C. for 30 min.
\+ Stress under which the original crack was developed.

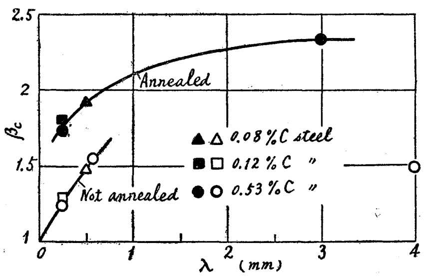


Fig. 5. Notch-factor against crack depth of round-cracked specimens of carbon steels.

[2] R. E. Peterson, "Stress-concentration phenomena in fatigue of metals", Trans. ASME, 55, 1933, p. 157.

The reason of the considerable decrease of the fatigue strength of post-annealed round-cracked specimens in comparison with that of the not annealed ones will be understood by considering that the work-hardened region at the end of the crack aroused during development of the original crack will be softened by annealing[3].

4. Comparison of the results with published data. To compare our results with those of published data the followings will be mentioned.

a) A. E. Flanigan and M. Kaufman[4] have reported the results of fatigue tests on all-weld-metal specimens (rotary cantilever type). The fatigue specimens were machined out of weld-metal deposited in U-groove at the mid-length of semi-killed A 285 C plate (E 6010 electrode). Fatigue limit of the all-weld-metal specimens having no microcracks was 30.8 kg/mm^2, whereas that of the specimens having a large number of microcracks induced by rapid water-quenching was reduced to 18.2 kg/mm^2. The average length of these microcracks, from the microphotographs of the typical microcracks in their paper, seems to be about 0.3 mm. Since the decrease of fatigue strength in this case will be mainly due to the notch-effect of the microcracks on the surfaces of specimens, the ratio 1.69 of these fatigue limits will be the notch-factor of the microcracks (0.3 mm in linear dimension) in weld-metal. This value of notch-factor coincides nearly with that of post-annealed round-cracked specimen with crack depth of 0.3 mm (Fig. 5).

b) D. J. McAdam and G. W. Geil[5] have examined the lowering of the fatigue limits (rotating cantilever type) of various steel specimens due to stressless corrosion under various conditions and have concluded that such lowering of fatigue limits must be attributed to stress concentration of sharp rootlike projections at the bottoms of rounded corrosion pits. These projections can be considered as minute cracks. The maximum size of pits with projection can be estimated from the photographs in their paper to be about 0.5 mm. The ratios of the fatigue strength of the corroded specimens to that of the not-corroded ones were $1.2 \sim 1.9$ which agree well with those of the round-cracked specimens with crack depth of about 0.5 mm or below (Fig. 5).

5. Conclusions.

The following conclusions will be obtained.

a) Cracks in carbon steels will be regarded as sharp notches. So far as the depth of crack is $0.25 \sim 0.5$ mm, notch-factors β_c of cracks are $1.3 \sim 1.5$ for specimens not-annealed after original cracks are made, whereas those

[3] T. Isibasi, "Strength and deformation of low carbon steel bars with a round-crack under statical and repeated loads", Mem. Fac. Engg., Kyushu Univ., 12, 1951, p. 281.

[4] A. E. Flanigan, M. Kaufman, "Microcracks and the low-temperature cooling rate embrittlement of welds", The Weld. Jour., 30, 1951, Res. Suppl., p. 613 s.

[5] D.J. McAdam, G. W. Geil, "Pitting and its effect on the fatigue limit of steels corroded under various conditions", Proc. A.S.T.M., 41, 1941, p. 696.

are $1.7 \sim 1.9$ for post-annealed specimens. β_c increases as the depth of crack deepens.

b) β_c of annealed carbon steels seems to be indifferent to their carbon contents.

c) The detrimental effects of post-annealing on the fatigue strength of round-cracked specimens were again confirmed[3).

(Received March 24, 1953)

Plate 1 ($\times 3$).

Plates 1 and 2 show some fractured surfaces of the round-cracked specimens. The outer dark part is original crack. Numbers in parentheses are specimen No.

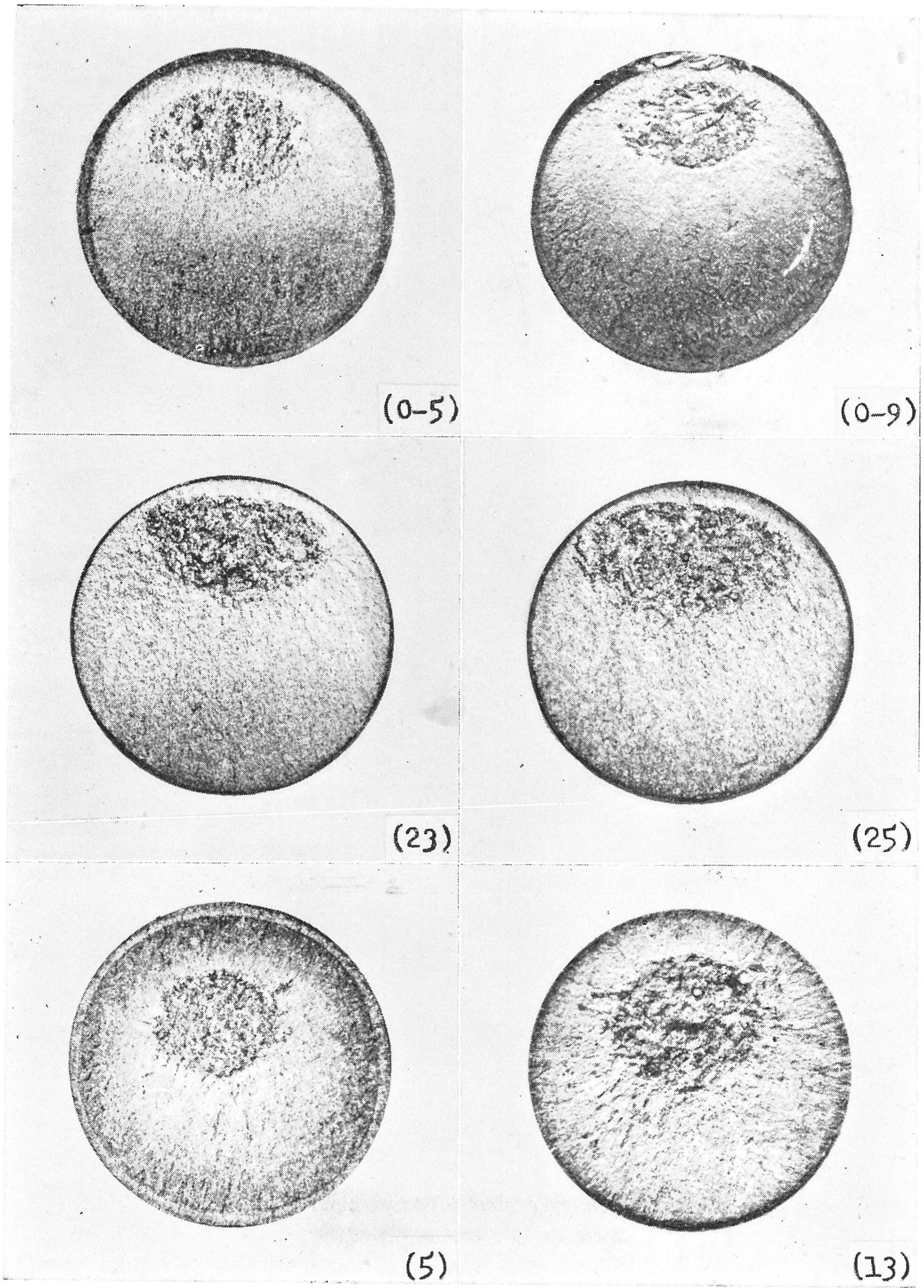


Plate 2 (×2.2).