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FATIGUE STRENGTH OF ALLOY STEEL BARS WITH A ROUND-CRACK*

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In order to know the notch-effects of minute crack as a stress-raiser on the fatigue strength of alloy steels, the fatigue strength of round-cracked specimens of nickel-chromium and chromium-molybdenum steels was measured under rotary bending stress. Detrimental effects of relieving the specimens of strain-hardened region at the tip of the crack on the fatigue strength of cracked specimens were also studied. Although the notch-factor β_c of the round-cracked specimens is a function of crack depth, increasing as the crack depth deepens, both alloy steels show about the same value of β_c for a given crack depth. The measured values of β_c are 2.3～3.5 for specimens of which the crack was made after heat treatment so far as the crack depths are 0.4～2.0 mm. For specimens of which the crack was made before heat treatment β_c are 3.1～4.6 so far as the crack depths are 0.4～1.0 mm.

1. Introduction. In a previous paper[1] we reported the notch-effects of minute crack, as a stress-raiser, on the fatigue strength of steels by measuring the fatigue strength of some carbon steel bars with a round-crack under rotary bending stresses.

In this work the fatigue strength of the round-cracked specimens of some alloy steels under rotary bending stresses is discussed.

2. Materials used and preparations of round-cracked specimens. The materials used are two sorts of alloy steels; nickel-chromium steel (SNC 1)** and chromium molybdenum steel (SCMo 90)**. Their chemical composition, mechanical properties and microstructures in the heat-treated states are shown in Table 1, in Table 2 and in Fig. 1(a) and (b), respectively.

All test-pieces of each material were taken from bars of 20 mm in diameter and 210 mm in length which were forged from round bars of 50 mm in diameter. After forging, the bars were grouped in two series; Series A and Series B.

The bars in Series A (SNC 1 and SCMo 90) were turned to make 60° V-grooved specimens as shown in Fig. 2(a) after the heat treatments shown in Table 1. The bars in Series B (SNC 1), after forging, were annealed

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1) T. Isibasi, T. Uryu, "Fatigue strength of carbon steel bars with round-crack," Rep. Res. Inst. App. Mech., Kyushu Univ., II, 1953, p. 65.

** SNC 1 and SCMo 90; Designation in JIS.

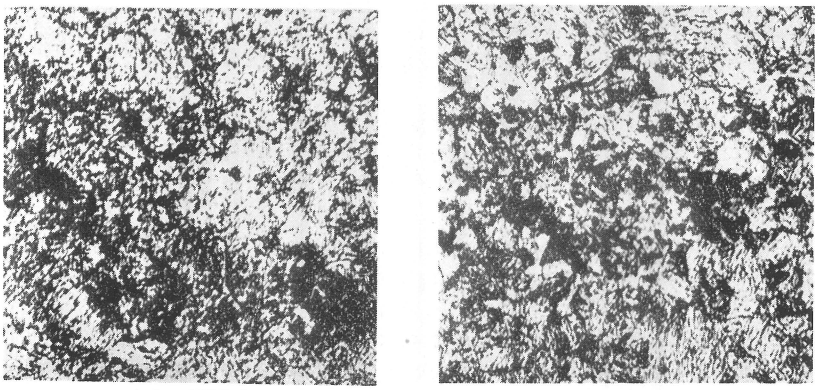
TABLE 1. Chemical composition of the alloy steels tested.

Alloy steel	Chemical composition, (%)								
	C	Si	Mn	P	S	Ni	Cr	Mo	Cu
Ni-Cr steel (SNC 1)	0.34	0.23	0.63	0.012	0.014	1.32	0.61	...	0.23
Cr-Mo steel (SCMo 90)	0.25~0.35	0.35	0.60	0 03	0.03	...	0.8~1.2	0.15~0.25	...

TABLE 2. Heat treatments and mechanical properties of the alloy steels tested.

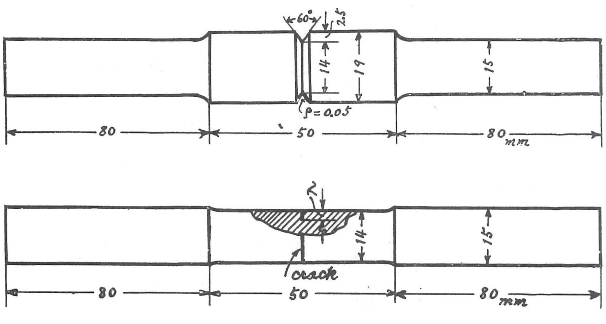
Alloy steel	Heat treatment		Mechanical properties, (kg/mm², %)					
	Quenching	Tempering	σ_S	σ_B	σ_T	φ	ϕ	H_B
Ni-Cr steel (SNC 1)	850° C, 1 hr, oil	600° C, 30 min, oil	78.8	90.5	151	17.1	58.1	252
Cr-Mo steel (SCMo 90)	850° C, 1 hr, oil	625° C, 30 min, oil	83.5	94.1	168	18.1	64.9	290

σ_S; yield strength at 0.2% offset, σ_B; tensile strength, σ_T; actual breaking stress, φ; elongation (gauge length 50 mm), ϕ; contraction of area, H_B; Brinell hardness number.



(a) SNC 1. (b) SCMo 90.

FIG. 1. Microphotographs of the alloy steels tested (× 200).



(a) 60° V-grooved specimen.

(b) Round-cracked specimen.

FIG. 2. Forms of specimens.

at 650° C for 1 hr. followed by cooling in the furnace and then were turned into the form shown in Fig. 2(a).

The notched specimens in both series were subjected, for some numbers of stress repetitions, to rotary bending stresses a little higher than their fatigue limits, in order to make a circumferential fatigue crack at the root of the machined notch. In this case, the stresses, expressed by the nominal bending stress on the minimum section at the root of the notch, and the numbers of stress repetitions were 21 kg/mm^2 and $20 \sim 40 \times 10^4$ cycles for SNC 1 (Series A); and 19 kg/mm^2 and $20 \sim 50 \times 10^4$ cycles for SCMo 90 (Series A); and 17 kg/mm^2 and $20 \sim 60 \times 10^4$ cycles for SNC 1 (Series B), respectively.

Although the depth of fatigue crack developed at the root of the notch depends roughly on the numbers of stress repetitions if the applied bending moment remains unchanged, to foresee correctly the crack depth without breaking the specimen, the testing machine was stopped many times in the course of the stress repetitions and the deflection of the middle point of each specimen due to statical bending moment was measured with a dial indicator by rotating the machine by hand. And from the increase of the deflection due to development of the fatigue crack the crack depth was estimated. At the same time, moreover, the specimen was pulled axially and the elongation of gauge length (20 mm, the notch lies between the gauge

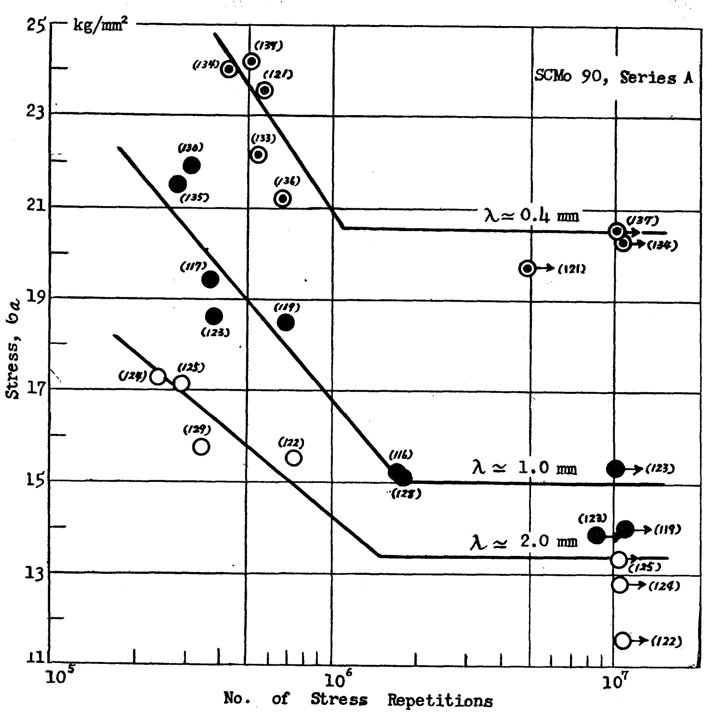


FIG. 3. S-N curves of round-cracked specimens (SCMo 90).

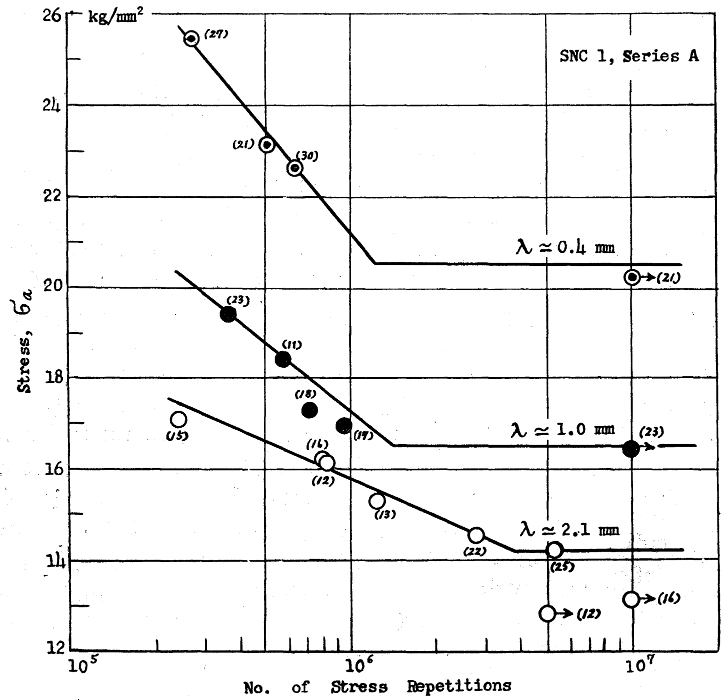


FIG. 4 (a).

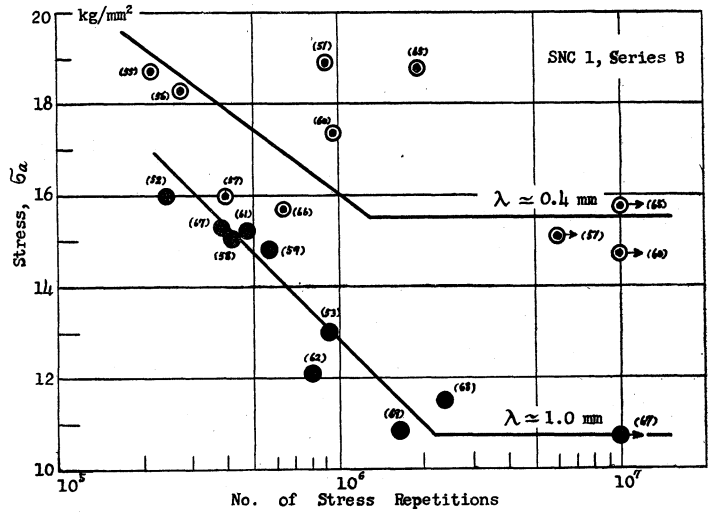


FIG. 4 (b).

FIG. 4 (a) and (b). S-N curves of round-cracked specimens (SNC 1).

marks) was measured. From the increase of the elongation the crack depth was estimated also. In this case, the maximum tensile load applied on the specimens was 850 kg or 1200 kg according to the estimated depth of the crack. The actual depth of the crack was, however, determined after each specimen was broken by fatigue.

When the crack depth was estimated to be a wanted depth, the machined notch of the specimens was turned off leaving the round-cracked specimens as shown in Fig. 2(b). The round-cracked specimens in Series A were heated at 300° C for 30 min. in the furnace in order to colour the cracked part so that we could determine the depth of the original crack, after the specimens were broken, by measuring the coloured part on the fractured surface. The specimens in Series A are sure to have a severly strain-hardened region at the tip of the crack. Since the round-cracked specimens in Series B were given the heat treatments shown in Table 1, the specimens in this series were relieved of the strain-hardened region at the tip of the crack due to cracking and the originally cracked part in the specimens was also coloured by such heat treatments.

3. Experimental results. The S-N curves of the specimens, of which the crack depths are nearly equal, are shown in Figs. 3, 4(a) and 4(b). In these Figs. arrows show specimens not broken and numbers in parentheses are specimen Nos. In some cases the specimens endured over 10^7 cycles of stress repetitions were subjected to higher stress levels 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. Referring to Fig. 5, which is a schematic representation of the broken surface, 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 on the battered region B was observed to start from the point P and its vicinity. Thus the nominal stress of the specimen was the nominal one at the point P calculated by assuming that the cracked part would support the compressive stress but not the tensile one while the stress distribution was linear as in ordinary bending.[2)]

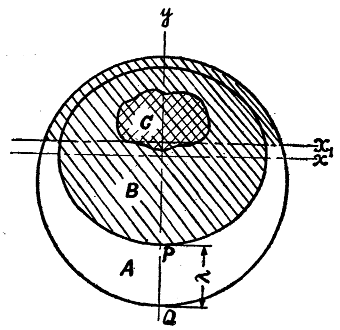


Fig. 5. Fractured surface (Schematic).

A; Original round-cracked region.
B; Battered region.
C; Final fractured region.

According to such assumptions, the

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

nominal tensile stress σ_1 at P is calculated by taking the section modulus of the shaded area about x_1-axis (neutral axis) shown in Fig. 5, regarding the region B as an elliptical form. On the other hand, the nominal compressive stress $-\sigma_2$ at P is obtained by inverting Fig. 5, in the same manner as in tension side. The round-cracked specimen will be considered, therefore, to be subjected to the nominal stress repeated between σ_1 and $-\sigma_2$ at the tip of the crack. In this case, the crack will act as a stress raiser different from the ordinary machined notch, that is, the stress concentration due to the crack may arise under the tensile stress σ_1 but not under the compressive stress $-\sigma_2$. However, the presence of the compressive stress $-\sigma_2$ at the tip of the crack will presumably have the appropriate effect on the lowering of the fatigue strength of the round-cracked specimen.

In this report, therefore, the nominal stress of the round-cracked specimen was taken to be $\sigma_a=(\sigma_1+\sigma_2)/2$, that is, the amplitude of the repeated nominal stress at the point P.

Some photographs of the fractured surfaces are shown in Plates 1 and 2 at the end of the paper.

The numerical results are summarized in Table 3 and the notch-factors β_c (ratio of the fatigue limit of the plain specimen to that of the cracked one) of the round-cracked specimens are plotted against the crack depths λ in Fig. 6. In Fig. 6, the notch-factors β_c on the annealed carbon steels are also shown in comparison with those on the present alloy steels. In the case of carbon steels, however, β_c are the values refered to σ_a instead of to σ_1 (in the previous report,[1] σ_1 was taken as the nominal one).

TABLE 3. Results of fatigue tests on round-cracked specimens of alloy steels (Rotary bending).

Alloy steel	Plain specimen		Round-cracked specimen					
	Dia., mm	Fatigue limit, kg/mm²	Dia., mm	Crack depth, λ, mm	Fatigue limit, σ_a, kg/mm²	Notch-factor, β_c	Cracking stress,† kg/mm²	Remarks
Ni-Cr steel (SNC 1)	10	48.5	14	0.4	21.0	2.31	21.0	Series A*
			〃	1.0	16.5	2.94	〃	
			〃	2.1	14.2	3.42	〃	
			14	0.4	15.5	3.13	17.0	Series B**
			〃	1.0	10.7	4.55	〃	
Cr-Mo steel (SCMo 90)	10	46.5	14	0.4	20.5	2.26	19.0	Series A*
			〃	1.0	15.0	3.10	〃	
			〃	2.0	13.4	3.47	〃	

† Stress under which the original crack was developed.

* Specimens were cracked after heat treatment.

** Specimens were heat-treated after cracking.

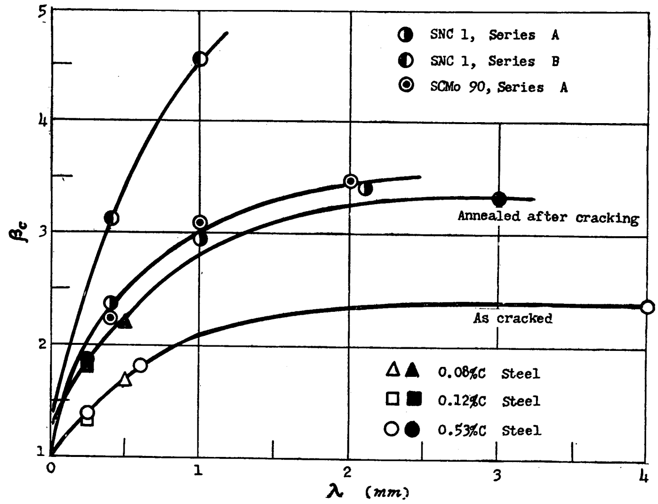


FIG. 6. Notch-factors *vs.* crack depths of round-cracked steel specimens.

4. Conclusion. The following conclusions will be obtained from the above experimental results.

1) The notch-factors β_c of the round-cracked specimens of Ni-Cr steel and Cr-Mo steel are nearly equal to each other for any given crack depth.

2) On these alloy steels, β_c are $2.3\sim3.5$ for specimens cracked after heat treatment, so far as the crack depths are $0.4\sim0.2$ mm. β_c increases as the crack deepens.

3) In the case of Ni-Cr steel, β_c are $3.1\sim4.6$ for specimens heat-treated after cracking, so far as the crack depths are $0.4\sim1.0$ mm. In this case β_c increases as the crack deepens.

4) Above fact, that is, the considerable decrease of the fatigue strength of the alloy steel specimens cracked *before* heat treatment as compared with that of the specimens cracked *after* heat treatment, shows the detrimental effect of relieving the specimens of strain-hardened region at the tip of the crack aroused during the development of the original crack. The same is true also in the case of carbon steels.[1]

5) β_c on these alloy steels are about 1.5 times of those on the carbon steels when the crack depths are equal to each other. But, the fatigue strength of the cracked alloy steel specimens is somewhat higher than that of the cracked carbon steel specimens.

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PLATE 1 (× 2.5).

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

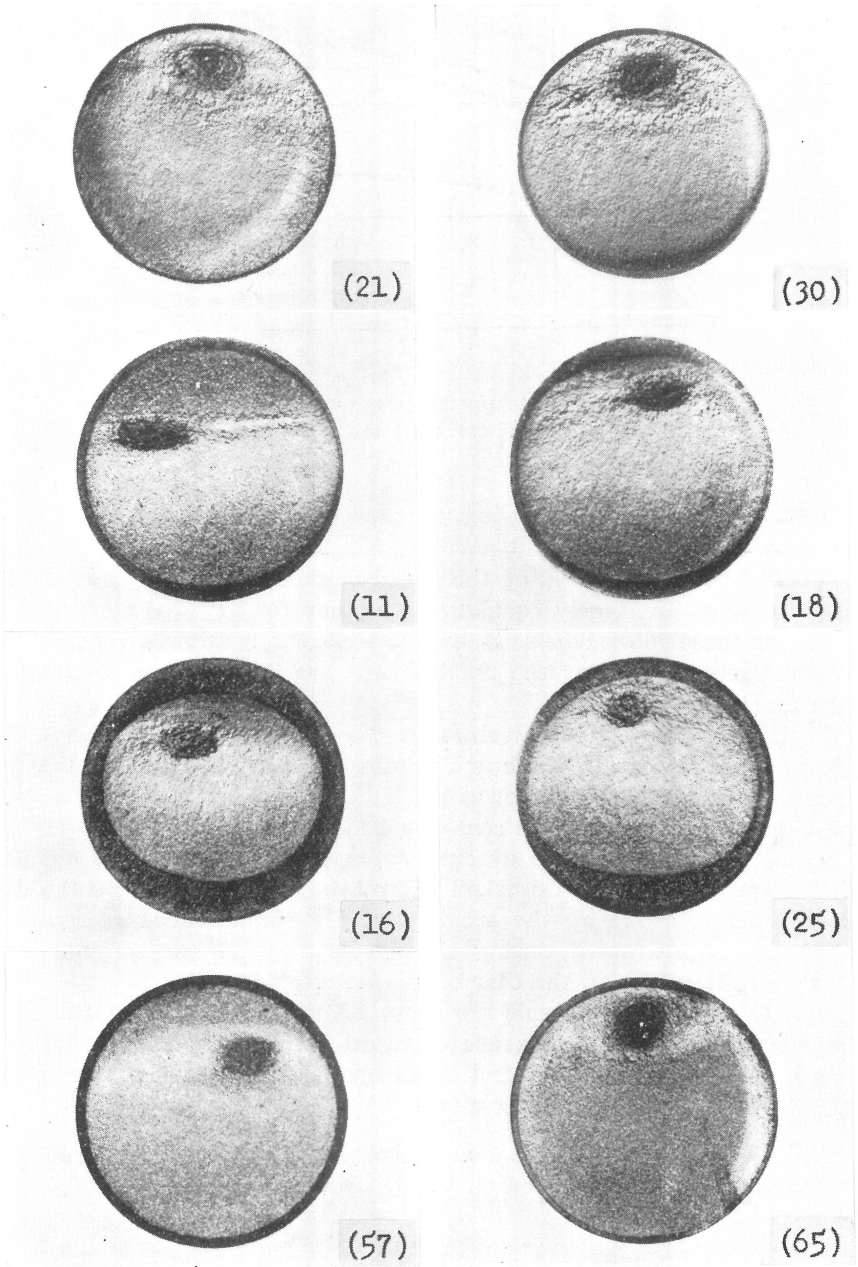

Plate 2 (× 2.5).