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https://doi.org/10.5109/7160852

出版情報：Reports of Research Institute for Applied Mechanics. 4 (16), pp.107-117, 1956-10. Research Institute for Applied Mechanics, Kyushu University

Reports of Research Institute for Applied Mechanics
Vol. IV, No. 16, October, 1956

ON THE NOTCH-FACTORS OF NOTCHED CARBON STEEL SPECIMENS*

By Tadasi ISIBASI and Tsunemi URYU

Abstract. Rotary bending tests of various carbon steel bars with a deep hyperboloidal groove or circumferential 60° V-groove were carried out and the fatigue limits for crack initiation as well as the usual fatigue limits of notched specimens were measured. From the results of these experiments it becomes clear that fatigue crack will be initiated at the root of notch when the elastic stress at the point distant ε_0 from the root of notch reaches the fatigue limit of the material, and the value of ε_0 may be regarded to be the constant value of 0.055 mm (0.05～0.06 mm) for carbon steels annealed or normalized, irrespective of the sharpness of notches or of carbon contents. Thus the notch-factor β based on the fatigue limit for crack initiation of carbon steels can be calculated from the elastic stress distribution around the root of notch.

1. Introduction. Concerning the fatigue strength of notched specimens under reversed stresses, in the case of sharply notched specimens, two kinds of fatigue strengths must be discriminated from each other. The one is the usual fatigue limit of which the repetition causes the specimen to crack but not to break off, and the specimen endured this fatigue limit has always a shallow non-propagating fatigue crack started at the root of the notch. Another kind of fatigue limit is the maximum nominal stress such that the specimen subjected to the repetition of this stress has no fatigue crack at the root of notch. The latter stress will be called the fatigue limit for crack initiation, and is smaller than the usual fatigue limit. The difference between these two kinds of fatigue limits decreases as the sharpness of the notch becomes less. They become equal to each other at the branch point.[1] In the specimen with a notch of smaller stress concentration factor than that of the branch point, the fatigue limit for crack initiation is equal to the usual one.

In order to appreciate the notch-effect on the fatigue strength of the notched specimen, the notch-factor β (fatigue strength reduction factor) based on the fatigue limit for crack initiation is more significant. The usual fatigue limit of the sharply notched specimen, of which stress concentration factor is greater than that of the branch point, will be determined by the characteristics of the resistance of propagation of the fatigue crack started at the root of the notch.

* Read before the Autumn Lecture Meeting in Tokyo, Japan Soc. Mech. Engs., Oct. 16, 1955.

1) T. Isibasi, "Fatigue and Fracture of Metals (in Japanese)," Yôkendô, Tokyo, 1954, p. 55.

In this work, rotary bending tests of various carbon steel specimens with deep hyperboloidal grooves or with circumferential 60° V-groove were carried out and two kinds of fatigue limits, mentioned above, were obtained. From the results of these experiments it is concluded that β based on the fatigue limit for crack initiation can be calculated, if the elastic stress distribution around the root of notch is known, irrespective of the kind of carbon steels.

2. Materials and specimens. The materials used were the annealed carbon steels, of which chemical composition and mechanical properties are shown in Table 1. All specimens were turned from rolled bars (of diameter 38 mm for 0.41 % C steel, 50 mm for 0.23 % C steel and 65 mm for 0.16 % C steel). Before turning, all bars were annealed at the temperatures shown in Table 1 and cooled in the furnace.

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

Steel	Annealing temp., °C	Chemical composition, %					Mechanical properties, kg/mm², %					
		C	Mn	Si	P	S	σ_{s0}	σ_{su}	σ_B	σ_T	φ	ψ
0.41 % C steel	830	0.41	0.74	0.17	0.04	0.03	39.3	37.6	62.7	105.4	30.4	50.4
0.23 % C "	860	0.23	0.46	0.27	0.02	0.03	30.9	28.3	47.9	81.6	34.1	54.0
0.16 % C "	890	0.16	0.82	0.14	0.02	0.03	31.9	28 5	46.7	89.7	36.4	60.5

σ_{s0} ; upper yield point, σ_{su} ; lower yield point,
σ_B ; tensile strength, σ_T ; actual stress at fracture,
φ ; elongation (gauge length 50 mm), ψ ; contraction of area.

The forms of notches of notched specimens were deep hyperboloidal grooves of various notch radii ρ, except the group of circumferential 60° V-grooved specimens of 0.16 % C steel. The diameter $2a$ of the notched section and the outside diameter D were, however, remained constant (Fig. 1). The values of $2a$, D and ρ for each specimen are shown in Table 2. Thus we were able to calculate the stress distribution around the root of the notch by means of the Neuber's method,[2] as long as the material remains elastic.

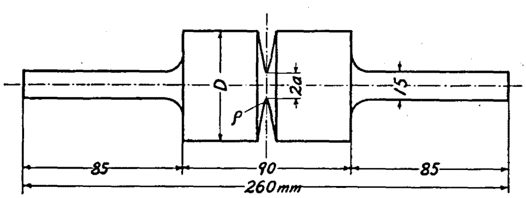


Fig. 1. Form of specimen with deep hyperboloidal groove.

To make hyperboloidal grooves, rough cutting bits and finishing bits with hyperbolic profiles were prepared. The profiles of finishing bits were

[2] H. Neuber, "Kerbspannungslehre," Julius Springer, Berlin, 1937.

precisely checked by projecting at a magnification of 50 times of its original dimension. First, with the rough cutting bit, the groove was turned about 0.4 mm larger than the finishing dimension, then the remaining part was turned off with the finishing bit carefully, to avoid excessive cold-working of the material at the root of the notch. The profile of the finished groove was also inspected by projection.

Table 2. Results of rotary bending tests on carbon steel specimens with deep hyperboloidal grooves and with 60° V-groove.

Steel	Dia., $2a$, mm	Outside dia., D mm	Root radious, ρ mm	$\frac{\rho}{a}$	Stress concent. factor, α	Fatigue limit, σ_w, kg/mm²	Notch-factor, β	ε_0, mm	Remarks
0.41 % C steel	12	—	∞	∞	1	$\sigma_{w0}=28.5$	1	—	Specimens were annealed at 650° C, for 30 min. after their final finishes.
	14	36	1.4	0.200	1.99	15.5	1.84	0.054	
	"	"	0.5	0.071	3.04	11.25	2.53	0.050	
	"	"	0.2	0.029	4 62	9.75 (9.25)	2.92 3.08	— 0.052	The decarburized layers at surfaces of specimens were nil.
0.23 % C steel	12	—	∞	∞	1	$\sigma_{w0}=21.75$	1	—	
	14	48	1.4	0.200	1.99	12.0	1.81	0.064	
	"	"	0.5	0.071	3.04	10.0 (8.5)	2.18 2.56	— 0.047	
	"	"	0.2	0.029	4.62	10.25 (7.1)	2.12 3.06	— 0.053	
	"	"	0.1	0.014	6.91	10.25 (6.5)	2.12 3.35	— 0.057	
0.16 % C steel	12	—	∞	∞	1	$\sigma_{w0}=22.25$	1	—	Specimens were annealed at 890° C, for 30 min. after their final finishes.
	12	60	3.0	0.500	1.48	15.75	1.41	0.061	
	"	"	1.0	0.167	2.14	11.5	1.93	0.049	
	"	"	0.5	0.083	2.84	9.75	2.29	0.060	The decarburized layers at surfaces of specimens were about 0.05 mm in depth.
	"	"	0.2	0.033	4.30	9.5	2.34	—	
	12	18	0.05	0.008	60° V-groove	10.75 (6.75)	2.07 3.30	— —	
0.16 % C steel[4]	12	—	∞	∞	1	$\sigma_{w0}=25.75$	1	—	Specimens were used in machined state.
	12	60	3.0	0.500	1.48	18.25	1.41	0.061	
	"	"	1.0	0.167	2.14	13.25	1.94	0.047	
	"	"	0.5	0.083	2.84	11.25	2.29	—	
	"	"	0.2	0.033	4.30	10.5	2.45	—	
0.62 % C steel[3]	12	—	∞	∞	1	$\sigma_{w0}=27.0$	1	—	Specimens were used in machined state.
	14	50	1.63	0.233	1.89	15.5	1.74	0.067	
	"	"	0.51	0.073	2.96	10.75	2.51	0.048	Material was annealed at 810° C. $\sigma_{su}=31.3$ kg/mm², $\sigma_B=68.9$ " .
	"	"	0.24	0.034	4.26	11.5 (9.1)	2.35 2.97	— 0.054	
	"	"	0.12	0.017	6.44	11.5 (8.5)	2.35 3.18	— 0.058	

It is known that the presence of such work-hardened layer as that due to machining, at the surface of the specimen, increases the fatigue strength of the specimen. This effect will be pronounced in the case of notched specimens and moreover the degree of work-hardening at the root of each notch will not be equal. It will be, therefore, desirable that the specimen is annealed to relieve of the work-hardened layer due to machining. In our experiments all the plain and notched specimens were, therefore, annealed after their final finishes, at the temperatures as shown in Table 2, held in a steel box tightly packed with steel cutting chips in order to prevent excessive oxidation of the surfaces of the specimens.

3. Results of the experiments. The summary of the results obtained by rotary bending tests is shown in Table 2. The results on 0.62 % C steel[3] and some parts of the results on 0.16 % C steel,[4] which were obtained for the specimens not annealed after their final finishes, have been already reported.

The fatigue limits σ_w of the notched specimens, shown in the 7th column in Table 2, are the nominal ones reckoned on the notched sections. In this

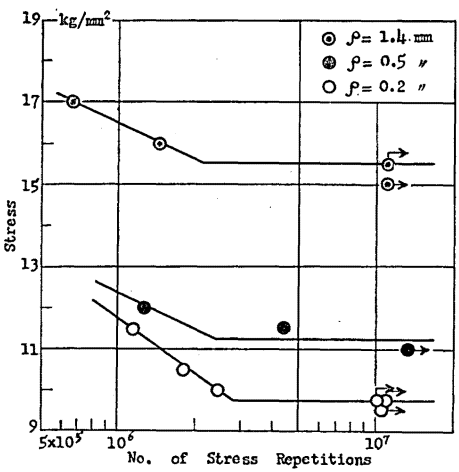


Fig. 2. S-N curves of hyperboloidal-grooved specimens (0.41 % C steel, specimens were annealed after final finish).

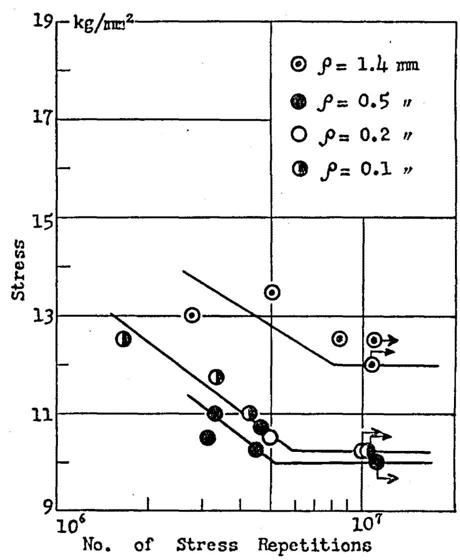


Fig. 3. S-N curves of hyperboloidal-grooved specimens (0.23 % C steel, specimens were annealed after final finish).

3) T. Isibasi, Preprint (in Japanese) of the 3rd Japan National Cong. for App. Mech., Sept. 8, 1953.

4) T. Isibasi, T. Uryu, E. Sato, "Fatigue strength of notched carbon steel bars with a crack (in Japanese)," Preprint of the 29th General Meeting (Tokyo), Japan Soc. Mech. Engs., April 2, 1952.

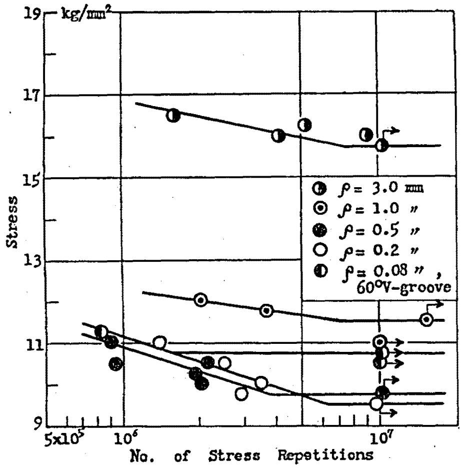


Fig. 4. S-N curves of hyperboloidal-grooved and 60° V-grooved specimens (0.16 % C steel, specimens were annealed after final finish).

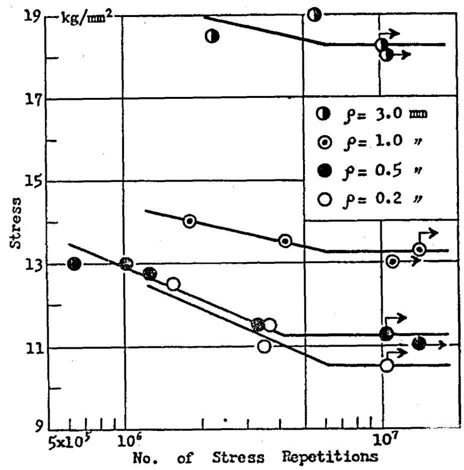


Fig. 5. S-N curves of hyperboloidal-grooved specimens (0.16 % C steel, specimens were not annealed after final finish).

column, σ_{w0} are the fatigue limits of the plain specimens. For notched specimens having such two fatigue limits as those mentioned before, two values of σ_w are shown; the values in parentheses are the fatigue limits for crack initiation and the others are the usual fatigue limits. In the case of 0.16 % C steel, however, the fatigue limits for crack initiation of the hyperboloidal-grooved specimens having such two fatigue limits were not determined.

The usual fatigue limits of the specimens were so determined that an increase of stress by 0.25 ~ 0.5 kg/mm² above the fatigue limits caused the specimens to break off before stress repetitions of 10^7 cycles were reached. (The speed of stress repetitions was about 2500 ~ 2700 rpm.). The obtained S-N curves of the notched specimens are shown in Figs. 2, 3, 4 and 5. In order to determine the fatigue limits for crack initiation, the specimens endured the usual fatigue limits were longitudinally sectioned and were microscopically examined whether any fatigue crack existed at the root of notch or not. When fatigue crack was found in specimens, its length was measured with a micrometer-microscope. The results are shown in Table 3. Some microphotographs of fatigue cracks at the root of the notch are shown in Plates 1 and 2 at the end of paper.

The 8th column, in Table 2, shows the notch-factors $\beta = \sigma_{w0}/\sigma_w$ (ratios of the fatigue limits of plain specimens to those of notched ones).

4. The fatigue limit for crack initiation. As a reliable explanation of the notch-effect in fatigue, it has been accepted that the total stresses

Table 3. Results of detections of fatigue cracks in specimens with deep hyperboloidal grooves.

Steel	Root radious, ρ mm	Stress reversed kg/mm²	Crack depth, λ_c mm	No. of photo. in Plates 1 and 2
0.41 % C steel	1.4	15.5*	0	
	0.5	11.0	0	
	0.2	9.75*	0.25	(1)
		9.5	0.23	
		9.25**	0	
0.23 % C steel	1.4	12.0*	0	
	0.5	10.0*	0.14	
		8.75	0.17	(2)
		8.5**	0	
	0.2	10.25*	0.28	(3)
		8.75	0.35	
		7.4	0.16	(4)
		7.1**	0	
	0.1	10.25*	0.45	(5)
		7.0	0.10	
		6.75	0.06	(6)
		6.5**	0	
0.16 % C steel	3.0	15.75*	0	
	1.0	11.5*	0	
	0.5	9.75*	0	
	0.2	9.5*	0.83	(7)
	0.05, (60° V-groove)	10.75*	0.23	(8)
		8.0	0 13	
		7.0	0.25	
		6.85	0.16	(9)
		6.75**	0	
0.16 % C steel[4]	3.0	18.25*	0	
	1.0	13.25*	0	
	0.5	11.25*	0.30	(10)
	0.2	10.5*	0.17	(11)

* The usual fatigue limit.
** The fatigue limit for crack initiation.

in a small volume of the material near the root of notch has predominant effect on the initiation of fatigue crack at that point[5]. Now, we assume that such small volume can be represented by the linear dimenson ε_0 measured from the root of notch in the direction of the maximum stress gradient (Fig. 6). Thus we consider that fatigue crack will be initiated at the root of the notch when the actual stress of the point distant ε_0 from the root of notch reaches the fatigue limit of the plain specimen.

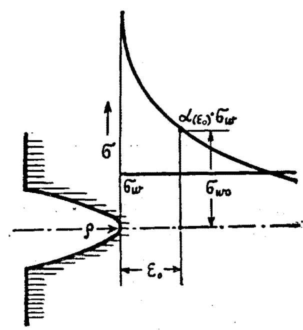


Fig. 6. Schematic representation of stress distribution at the root of notch.

Accordingly, the fatigue limit for crack initiation of notched specimens can be expressed in the following form;

$$\sigma_w = \sigma_{w_0} / \alpha_{(\varepsilon_0)}\,, \qquad (1)$$

where, $\alpha_{(\varepsilon_0)}$ is the elastic stress concentration factor of the point distant ε_0 from the root of notch.

For the specimens with deep hyperboloidal grooves, values of ε_0 are able to be calculated since the elastic stress distributions in the

[5] T. Isibasi, "On the fatigue limits of notched specimens," Memoirs Faculty of Engg., Kyushu Univ., 11, 1948, p. 1.

Table 4. Results of rotary bending tests on carbon steel specimens with deep hyperboloidal grooves.[6), 7)]

Steel	Root radious, ρ, mm	Stress concent. factor,* α	Fatigue limit,** σ_w, kg/mm²	Notch-factor, β	ε_0, mm	Mechanical properties, kg/mm²
0.219 % C steel, annealed	∞	1	$\sigma_{w0}=20$	1	—	
	2.4	1.58	14	1.43	0.105	$\sigma_{su}=21.2$
	1.2	1.99	11	1.82	0.053	$\sigma_{s0}=22.4$
	0.6	2.63	10	2.00	—	$\sigma_B=42.2$
	0.3	3.57	11.5	1.74	—	
	0.15	4.93	11	1.82	—	
0.219 % C steel, normalized	∞		$\sigma_{w0}=22$	1	—	
	2.4		14	1.57	—	$\sigma_{su}=25.1$
	1.2		11.5	1.92	0.024	$\sigma_{s0}=27.8$
	0.6		10	2.20	0.056	$\sigma_B=45.3$
	0.3		11.5	1.92	—	
	0.15		10.5	2.09	—	
0.252 % C steel, annealed	∞		$\sigma_{w0}=21$	1	—	
	2.4		14	1.50	0.057	$\sigma_{su}=24.5$
	1.2		12	1.75	0.077	$\sigma_{s0}=26.3$
	0.6		11	1.91	—	$\sigma_B=47.1$
	0.3		9	2.33	—	
	0.15		8.5	2.47	—	
0.252 % C steel, normalized	∞		$\sigma_{w0}=23$	1	—	—
	0.6		10.5	2.19	0.057	
	0.3		9	2.56	0.060	
	0.15		8.5	2.71	—	
0.377 % C steel, annealed	∞		$\sigma_{w0}=26$	1	—	
	2.4		17.5	1.49	0.062	
	1.2		15	1.73	0.083	$\sigma_{su}=32.5$
	0.6		11.5	2.26	0.049	$\sigma_B=61.4$
	0.3		12	2.17	—	
	0.15		11	2.37	—	
0.377 % C steel, normalized	∞		$\sigma_{w0}=27$	1	—	
	2.4		18	1.50	0.051	$\sigma_{su}=35.1$
	1.2		15	1.80	0.059	$\sigma_B=64.1$
	0.6		11.5	2.35	0.036	
	0.15		11	2.46	—	
0.756 % C steel, annealed	∞		$\sigma_{w0}=27$	1	—	
	2.4		17	1.59	—	$\sigma_{su}=32.1$
	1.2		14	1.94	—	$\sigma_B=77.3$
	0.6		12	2.25	0.049	
	0.3		10	2.70	0.049	
	0.15		9	3.00	0.052	
0.756 % C steel, normalized	∞		$\sigma_{w0}=30$	1	—	
	2.4		18	1.67	—	$\sigma_{su}=37.7$
	1.2		15	2.00	—	$\sigma_B=85.3$
	0.6		13.5	2.22	0.053	
	0.3		10	3.00	0.029	
	0.15		10	3.00	0.051	

* For all the notched specimens, $2a=12$ mm and $D=48$ mm.

** All the specimens were used in machined state.

specimens are known.[2] The values of ε_0 obtained are shown in the 9th column in Table 2. We see, in this column, the values of ε_0 are about 0.05 ~ 0.06 mm, irrespective of the sharpness of notches or of carbon contents of steels. The mean value of ε_0 is 0.055 mm.

The other experimental results of rotary bending tests of various carbon steel specimens with deep hyperboloidal grooves of various notch radii have been reported previously by A. Ono and M. Ono.[6),7)] Those experimental results are summarized and shown in Table 4. The 4th column in this Table shows the usual fatigue limits of the specimens. In this case, it was not examined whether the fatigue cracks were present in the specimens endured those usual fatigue limits. It is not, therefore, clear that the fatigue limits obtained are equal to those for crack initiation when the notches become sharper. Regarding, however, the fatigue limits obtained to be equal to those for crack initiation the values of ε_0 were calculated by (1).

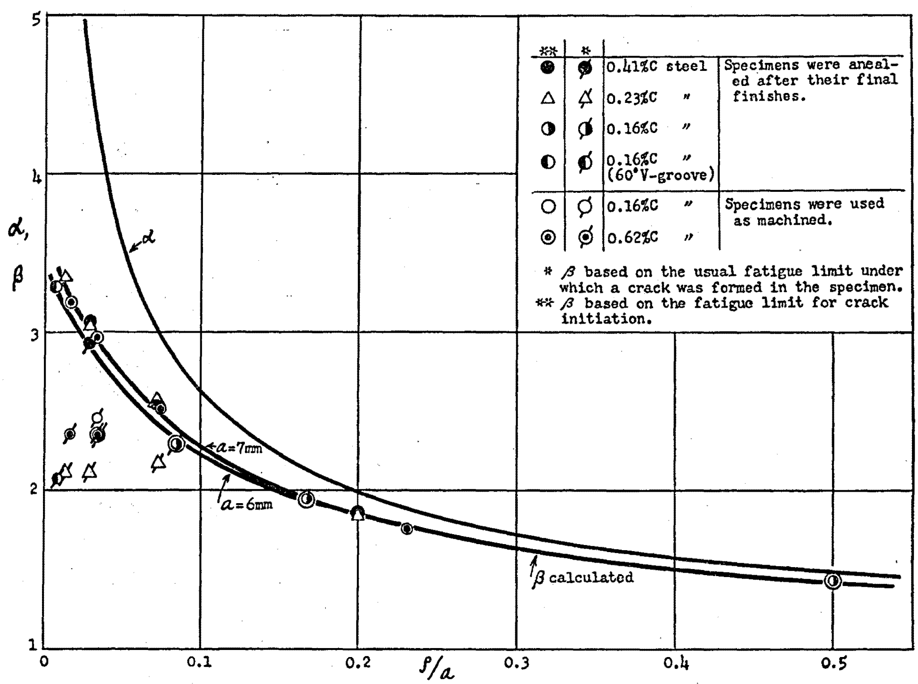


Fig. 7. β *vs.* ρ/a of hyperboloidal grooved specimens.

6) A. Ono and M. Ono, "Experimental investigation of the effect of notch on the fatigue strength of steel (in Japanese)," Trans. Japan Soc. Mech. Engs., 5, 1939, p. 167.

7) A. Ono and M. Ono, "Further experiments on the effect of notch on the fatigue of steel (in Japanese)," Trans. Japan Soc. Mech. Engs., 7, 1941, p. 20.

8) A. Ono, "Effect of diameter on notch-coefficient of rotary bending test piece," Proc. Japan Academy, 27, 1951, No. 8, p. 445.

9) A. Hikata, "The size effect in fatigue of notched steel specimens loaded under reversed direct stress," Government Mech. Laboratory Bulletin, No. 2, Tokyo Japan, 1954.

They are shown in the 6th column in Table 4. In this case, the mean value of ε_0 was 0.055 mm also.

From the experimental facts mentioned above, it can be concluded that the fatigue limit for crack initiation of the notched specimen can be expressed by Equation (1), in which ε_0 is a constant equal to 0.055 mm (0.05 ~ 0.06 mm) for carbon steels annealed or normalized, irrespective of the sharpness of notches or of carbon contents of steels.

Thus the notch-factor β based on the fatigue limit for crack initiation can be expressed as follows;

$$\beta \doteqdot \sigma_{w_0}/\sigma_w \doteqdot \alpha_{(\varepsilon_0)} . \quad (2)$$

From Equation (2), we are able to calculate β when the elastic stress distribution at the root of the notch is known. The fatigue limit for crack initiation of the notched specimen is also determined when the fatigue limit of the plain specimen is known. In Fig. 7, the experimental values of β as well as the curves of β obtained by Equation (2) using $\varepsilon_0 \doteqdot 0.055$ mm and the curve of α are plotted against ρ/a of the specimens.

It must be remarked here that the size effect of notched specimens on their fatigue strength will be reasonablly explained by regarding the value of ε_0 as constant and independent of the size of the specimens.[8), 9)]

5. Conclusions. Following conclusions will be obtained from the above results.

1) The fatigue limits for crack initiation as well as the usual fatigue limits of various carbon steel specimens with deep hyperboloidal grooves and with 60° V-groove were obtained (Table 2).

2) The fatigue limit for crack initiation of the notched specimen may be expressed by Equation (1); that is, a fatigue crack will be initiated at the root of notch when the elastic stress of the point distant ε_0 from the root of notch reaches the fatigue limit of plain specimen.

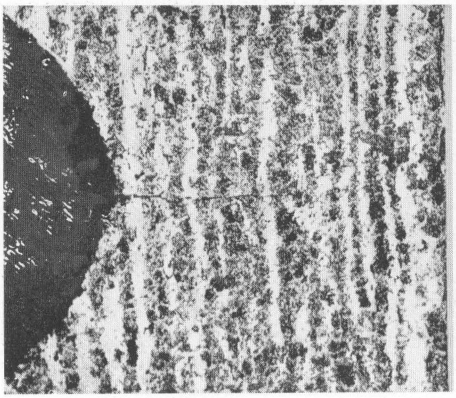
3) ε_0 may be considered to be the thickness of a surface layer concerned in the origin of fatigue cracks. And the value of ε_0 may be regarded to be 0.055 mm (0.05 ~ 0.06 mm), for carbon steels annealed or normalized, irrespective of the sharpness of notches or of carbon contents of steels.

4) The notch-factor β based on the fatigue limit for crack initiation of carbon steels can be calculated from the elastic stress distribution around the root of the notch.

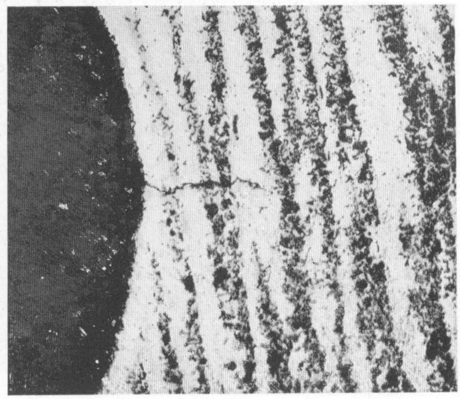
(Received August 11, 1956)

Plate 1.

Nos of photographs in Plates 1 and 2 are referred to those in Table 3.

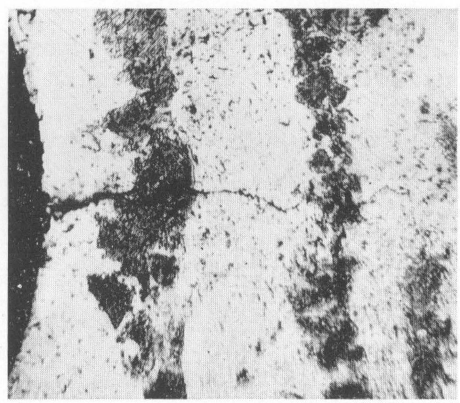


(1) × 100.

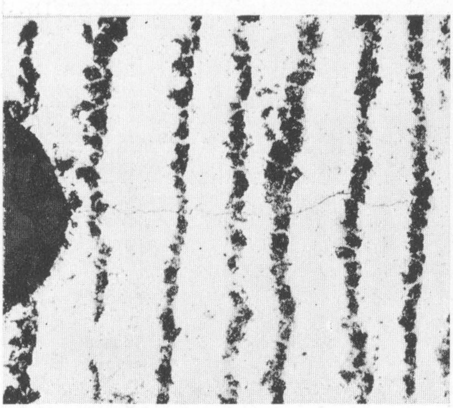


(2) × 100.

(3) × 100.



(4) × 300.



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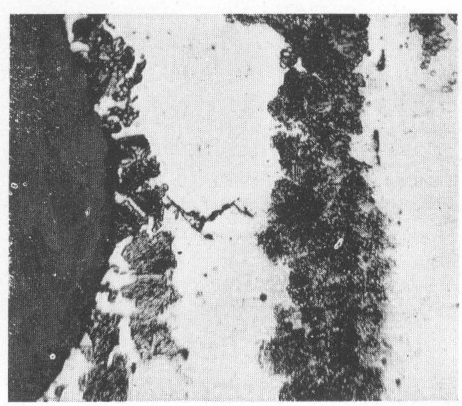
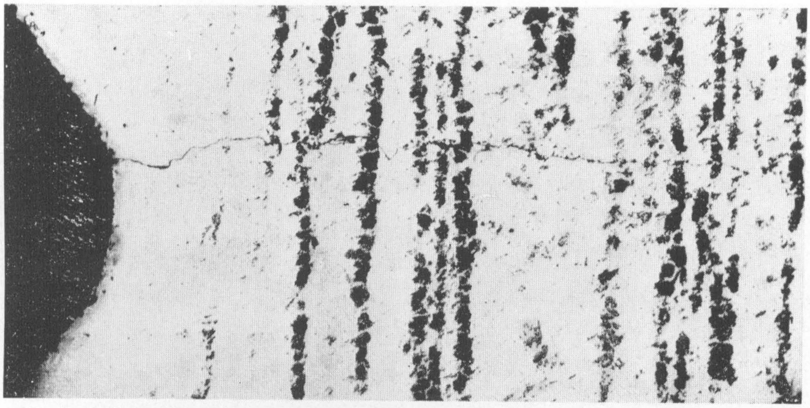
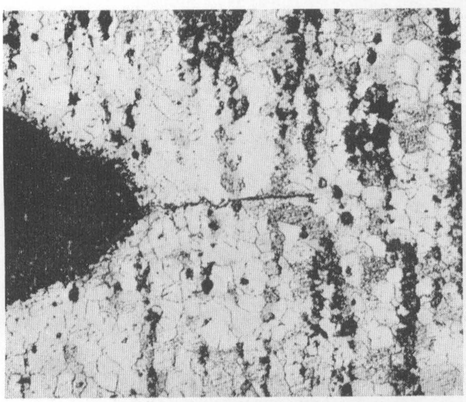


(6) × 300.

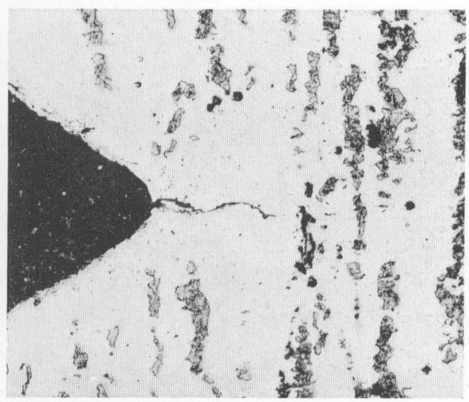
Plate 2.



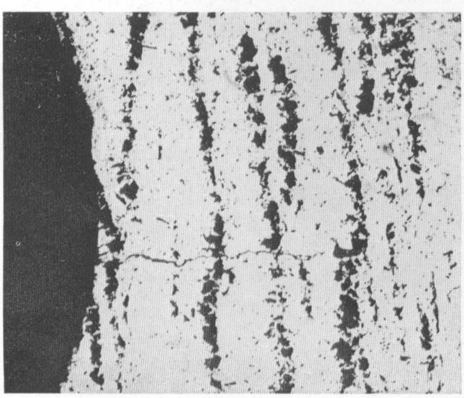
(7) × 100.



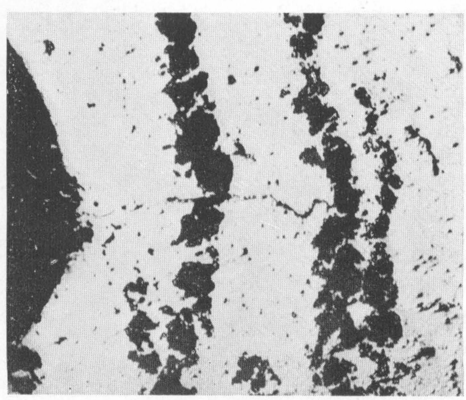
(8) × 100.



(9) × 100.



(10) ×100.



(11) × 200.