ON THE HARDNESS CHANGE IN MILD STEELS DUE TO REVERSED STRESSES AND THE PLASTIC REGION AROUND TIP OF FATIGUE CRACK

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ON THE HARDNESS CHANGE IN MILD STEELS DUE TO REVERSED STRESSES AND THE PLASTIC REGION AROUND TIP OF FATIGUE CRACK*

By Tsunemi URYU

1. Introduction. Concerning the hardness changes in carbon steels subjected to repeated stresses, a number of experimental studies have been carried out.[1)~5)] From the results of those studies it has been known that the hardness of a carbon steel increases under repeated stresses beyond a certain stress, and that the degree of hardening depends on the applied stresses and on the number of stress repetitions while the hardness tends to converge toward a maximum value at the last stage of fatigue life. It has been also reported that in the case of rotary bending stressing the minimum stress from which the increase in hardness of a carbon steel begins to take place is a little lower than the fatigue limit of that steel.[1),2)] Such hardness changes as due to stresses near the fatigue limit are, however, in a small degree, so this matter seems not to be clear so far.

In the present study, in order to see about the hardness changes in mild steels (*plain specimens*) subjected to rotary bending stresses near their fatigue limits, the micro-hardness tests were made discriminately on each of the ferrite and pearlite grains in the steels. Moreover, by means of the micro-hardness test, the magnitude of the plastic region around the tip of the fatigue crack in a mild steel (*notched specimens*) was evaluated.

2. Experiments on plain specimens.

(a) *Plain specimens and fatigue tests.* The materials used were three kinds of the annealed mild steels and their chemical composition and mechanical properties are shown in Table 1. The form and dimensions of plain specimens

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* Read before the 34th General Meeting (Tokyo) of Japan Soc. Mech. Engs., April 3, 1957.

1) R. Yamada, Y. Matsuoka, "On the change of mechanical properties in metals under repeated stress and on the recovery of fatigue (in Japanese)," Jour. Japan Soc. Mech. Engs., 37, 1934, p. 273.

2) F. Oshiba, "On the change of hardness caused by repeated stress and the effect of ageing on its recovery (in Japanese)," Jour. Japan Inst. Metals, 3, 1939, p. 283.

3) T. Yokobori, "Fatigue fracture of steel," Jour. Phys. Soc. Japan, 6, 1951, p. 81; "Damage as an initial stage of fatigue fracture," *ibid.*, 8, 1953, p. 806.

4) N. Oda, K. Nishioka, "On the large-type fatigue testing machine and the experimental results (in Japanese)," Jour. Japan Soc. Mech. Engs., 58, 1955, p. 718.

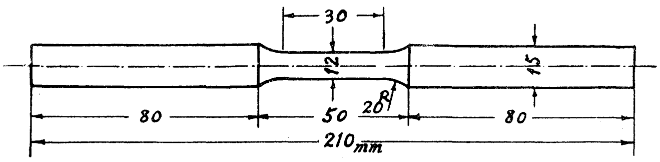
5) Z. Andō, S. Nisino, "The effect of rotatory bending stress on the hardness of low carbon steel (in Japanese)," Trans. Japan Soc. Mech. Engs., 23, 1957, p. 495; "The effect of completely reversed torsional stress on the hardness of low carbon steel (in Japanese)," *ibid.*, 23, 1957, p. 854.

for rotary bending tests are given in Fig. 1(a). After the surfaces of the specimens were mechanically polished down to 0/5 grade of emery paper, all the specimens were annealed at the temperatures of 650°C for 30 min. for 0.20% C and 0.23% C steels, and of 700°C for 30 min. for 0.12% C steel, in order to relieve the strain-hardened surface layers due to machining and polishing, where they were kept together with steel cutting chip in a tight steel box in order to prevent excessive oxidation of their surfaces.

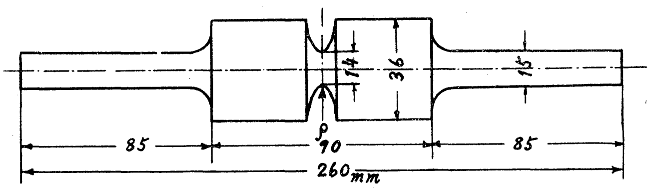
TABLE 1. Chemical composition and mechanical properties of the mild steels used (Annealed state).

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	σ_{w0}
0.20% C steel	900	0.20	0.53	0.01	0.02	0.03	23.5	22.3	39.2	77.5	46.7	61.8	17.25
0.23% C steel	860	0.23	0.46	0.27	0.02	0.03	30.9	28.3	47.9	81.6	34.1	54.0	21.75
0.12% C steel	900	0.12	0.38	0.12	0.02	0.03	30.8	26.0	39.7	86.4	42.2	67.6	21.0

σ_{s0} ; upper yield point, σ_{su} ; lower yield point,
σ_B ; tensile strength, σ_T ; actual breaking stress,
φ ; elongation (gauge length, 50 mm), ψ ; contraction of area,
σ_{w0} ; fatigue limit under rotary bending of plain specimen.



(a) Plain specimen.



(b) Deep hyperboloidal-grooved specimen ($\rho = 0.2$ and 0.5 mm).

Fig. 1. Forms and dimensions of specimens.

Then, the specimens were subjected to rotary bending tests in the ordinary way to determine the S–N curves. The speed of stress repetitions was about 2500~2700 rpm. The fatigue limits obtained are shown in the last column in Table 1.

(b) *Micro-hardness tests.* After the fatigue tests were performed, for the facility of further treatments, the test-pieces, 15~20 mm in length, for micro-hardness tests were cut from the smooth portions of the fatigued specimens. In the case of broken specimens, such test-pieces were taken as distant as possible from the fractured sections of the specimens. Before micro-hardness tests, the surfaces of these test-pieces were electrolytically polished in orthophosphoric acid solution with oxalic acid and gelatin, where the surface layers of 0.003~0.005 mm in thickness were resolved.

Then, the micro-hardness of each of the ferrite and pearlite grains on such electro-polished surfaces was measured without further etching since the micro-structures of the surfaces were revealed due to the above electrolytic polishing. The Shimadzu micro hardness tester was employed, the indenter being a standard Vickers-type pyramidal diamond. In the present case, the loads applied to the indenter were 25 gr. and 50 gr. for the ferrite and pearlite, respectively, so that the diagonal length of indentations was roughly 20 μ in both cases of the ferrite and pearlite. Especially for the pearlite, therefore, the tests were made with larger grains than 20 μ in size. The number of measurements made was twenty for each of the ferrite and pearlite in every test-piece. Some photographs of indentations in the ferrite and pearlite grains are shown in Fig. 5(a), (b) and (c) at the end of the paper.

(c) *Experimental results.* The results of micro-hardness tests as well as prior fatigue tests are summarized in Table 2 and shown graphically in Fig. 2. Each of the mean hardness values given in fifth and seventh columns in Table 2 is based on twenty measured values as mentioned above.

TABLE 2. Results of micro-Vickers hardness tests on the mild steels subjected to rotary bending stresses.

Steel	Specimen number	Stress, kg/mm^2	Number of stress repetitions,* $\times 10^6$	Hardness of ferrite (25 gr. load)		Hardness of pearlite (50 gr. load)	
				Mean hardness number	Standard deviation	Mean hardness number	Standard deviation
0.20% C steel	5	0	0	115	3.4	240	19.1
	6	0	0	115	4.6	235	16.2
	4	17.25	10.3 (NB)	114	4.9	243	10.9
	1	17.5	3.3 (B)	122	4.5	243	11.4
	2	18.0	2.2 (NB)	123	6.3	242	16.4
	3	18.5	1.5 (B)	122	3.0	238	10.0
0.23% C steel	0-4	0	0	122	3.3	232	21.7
	0-9	0	0	125	4.0	232	18.0
	0-7	20.0	10.1 (NB)	124	4.4	234	21.3
	0-1	21.5	14.9 (〃)	125	4.9	230	19.2
	0-2	21.75	12.1 (〃)	125	5.9	236	14.7
	0-5	22.0	4.6 (B)	133	5.4	233	20.1
	0-8	23.0	1.0 (〃)	133	6.7	229	12.8
	0-3	24.0	1.2 (〃)	136	5.3	229	16.7
	0-6	27.0	0.2 (〃)	136	6.2	233	21.9
0.12% C steel	18	0	0	129	5.8		
	26	0	0	127	6.0		
	19	19.5	10.0 (NB)	129	5.5		
	25	20.5	23.0 (〃)	133	3.9		
	24	21.0	10.2 (B)	130	4.3		
	30	21.0	13.2 (NB)	133	4.9		
	32	22.0	2.0 (B)	141	7.2		
	28	23.0	4.3 (〃)	141	8.3		
	23	23.0	2.7 (〃)	141	8.3		
	33	23.0	1.8 (〃)	140	7.3		

* (NB) indicates that specimen did not break; (B) indicates that specimen broke.

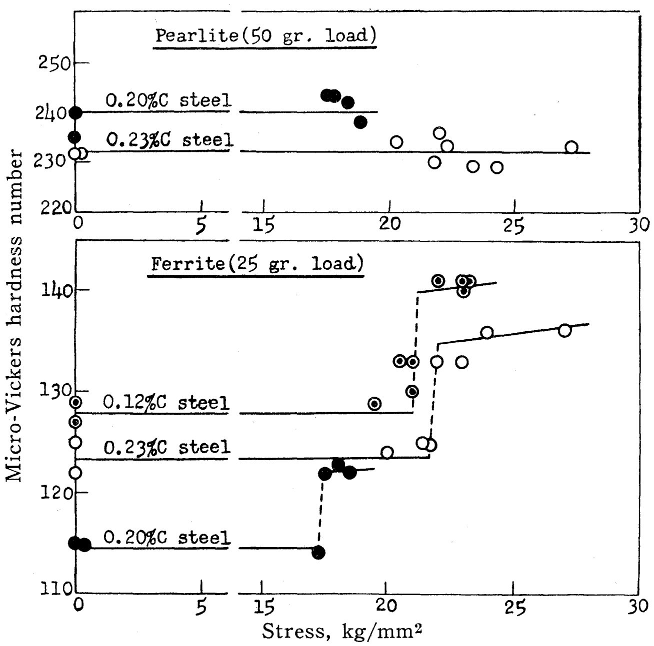


Fig. 2. Hardness changes of the ferrite and pearlite in mild steels subjected to rotary bending stresses.

As seen in Fig. 2, the mean hardness value of the ferrite is regarded to be nearly unchanged up to the fatigue limit and to increase abruptly from a stress just above the fatigue limit. On the other hand, the mean hardness value of the pearlite does not increase under the stresses near the fatigue limit (below the lower yield point in the present stress range).

As to the above hardness changes of the ferrite, the followings will be considered. In the case of stresses up to the fatigue limit, the number of slipped ferrite grains and the density of slip bands in the slipped grains are so less that the increase in the mean hardness value of the ferrite is not observed. In the case of stresses beyond the fatigue limit, on the other hand, such slipped grains and slip bands increase abruptly (to cause eventually the fatigue fracture of the specimen) so that the increase in the mean hardness value of the ferrite takes place as a result of strain-hardening. This viewpoint will be also expected, such as, from the results of microscopic examinations by F. Wever *et al.*[6]

(d) *Comparison with static tension tests.* In order to compare the increase in hardness of the ferrite due to repetitions of stresses just above the fatigue limit with that due to static tension, a test was made on 0.20% C steel. The specimen for tension test was a round bar of 14 mm in dia., of which the mechanical polishing, subsequent stress relieving annealing and final electrolytic polishing were carried out by the same methods as in the case of the fatigue specimens. After electrolytic polishing, the specimen was pulled by a tensile testing machine and the micro-hardness tests for ferrite grains on the specimen surface were made under unloading after loading to certain stresses, successively, in the course of drawing the stress-strain diagram.

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[6] F. Wever, M. Hempel, A. Schrader, "Metallographische Untersuchungen über Verformungserscheinungen an der Oberfläche biegewechselbeanspruchter Proben aus St 37," Arch. Eisenhuttenw., 26, Heft 12, 1955, s. 739.

The results obtained are summarized in Table 3 and in Fig. 3. Also in this case, the load applied to the indenter of the hardness tester was 25 gr. and each of the mean hardness values shown in Table 3 is based on twenty measured values. It is seen that the increase in hardness of the ferrite due to repetitions of a stress just above the fatigue limit corresponds to that due to the conventional strain of about 3%. This is interesting in connection with a known fact that the upper yield point and yield point elongation of mild steels fatigued under reversed stresses just above the fatigue limits disappear in subsequent tension test.[7]

TABLE 3. Results of micro-Vickers hardness tests (25 gr. load) for ferrite in 0.20% C steel subjected to static tension.

Stress,* kg/mm²	Strain,* %	Mean hardness number	Standard deviation
0	0	115	3.4
22.9	2.0	119	5.1
26.4	2.8	121	5.6
28.7	3.7	124	6.4
32.6	5.6	131	5.4
34.8	7.3	134	5.6
37.2	10.2	140	6.0
38.9	14.2	146	7.2
39.3	17.8	148	8.8

* Stress and strain are conventional ones.

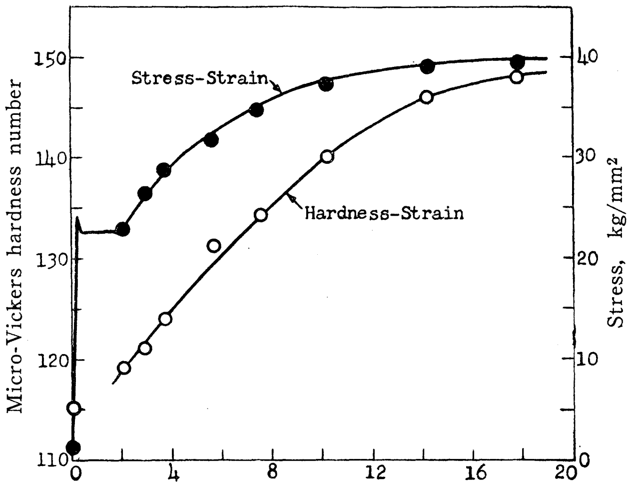

Fig. 3. Hardness changes of the ferrite in 0.20% C steel due to static tension.

3. Experiments on fatigue cracks in notched specimens. In the previous paper,[8] the fatigue strength of a compound-notched carbon steel bar with a circumferential crack at the root of the machined groove was calculated under a consideration that the fixed small plastic region (being represented

[7] e. g., K. Memmler, K. Laute, "Dauerversuche an der Hochfrequenz-Zug-Druck-Maschine (Bauart Schenck)," Forschungsarbeiten, VDI. Heft 329, 1930.

[8] T. Uryu, "Fatigue strength of notched carbon steel specimen with a circumferential crack at the notch root," Rep. Res. Inst. Appl. Mech., Kyushu Univ., V, 1957, p. 129.

by ε_c) precedes the tip of a developing fatigue crack, where the stresses in such plastic region exceed the fatigue limit of the plain specimen. In this calculation, a suitable value of ε_c for a material had to be assumed.

From the above-mentioned results of micro-hardness tests for plain specimens, however, it may be expected that the hardness of ferrite grains in the region ε_c will be to increase. Therefore, an estimation of the magnitude of ε_c by means of micro-hardness tests was done on 0.20% C steel.

(a) *Preparations of test-pieces.* In order to have the test-pieces with fatigue cracks for micro-hardness tests, two kinds of deep hyperboloidal-grooved specimens of 0.20% C steel were prepared (Fig. 1(b)), which were annealed at 650°C for 30 min. in order to relieve the work-hardening due to machining. These notched specimens were subjected to rotary bending stresses. Their S–N curves obtained are shown in Fig. 4, in which the stresses are the nominal ones based on the minimum sections at the roots of the grooves.

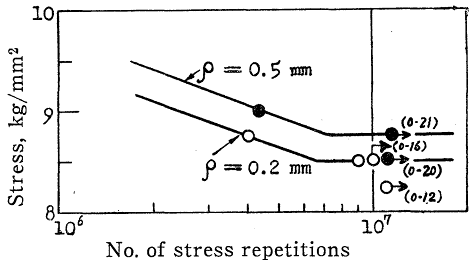

Fig. 4. S–N curves of deep hyperboloidal-grooved specimens of 0.20% C steel under rotary bending. (Arrows show that specimens did not break, and numbers in parentheses are specimen numbers.)

In the present case, the notched specimens which endured 10^7 cycles of their fatigue limits or certain stresses below the fatigue limits, have always shallow circumferential non-propagating fatigue cracks at the roots of the grooves.[8] Therefore, each of the notched specimens endured was sectioned longitudinally, to provide a diametric longitudinal section with fatigue cracks for micro-hardness measurements. The machined grooves of these test-pieces cut out were filled with solder to protect the roots of the grooves during further treatments. Then, these longitudinal sections were polished with emery paper and buffed with chromic oxide, and then polished electrolytically in orthophosphoric acid solution. The thickness of surface layers resolved by the final electrolytic polishing was about 0.05 mm and over.

(b) *Micro-hardness tests and the results.* The results of micro-hardness measurements for ferrite grains around the non-propagating fatigue cracks at the roots of the grooves are shown photographically in Fig. 6(a)~(f) at the end of the paper. In these photographs, numbers attached to the indentations are hardness numbers and the retouched thick curves show the profiles of the roots of the grooves. Moreover, the distributions[9] of the maximum elastic stress, which would act at the minimum sections of the roots of the grooves before the fatigue cracks were formed, are presented; where σ_{w0} is the fatigue limit of the plain specimen.

Although the region of hardened ferrite grains around the cracks is not

[9] Calculated by means of Neuber's method; H. Neuber, "Kerbspannungslehre" Julius Springer, Berlin, 1937.

so clearly distinguishable in the above photographs, such hardened region is seen to be inside of roughly 0.1 mm around the cracks. Therefore, the mean hardness values of the measured ones inside and outside of 0.1 mm around the crack are calculated and shown in fifth and eighth columns in Table 4, respectively. The order (0.1 mm and less) of ε_c estimated from the results of the present hardness tests is in agreement with that assumed in the previous report.[8]

TABLE 4. Results of micro-Vickers hardness tests (25 gr. load) for ferrite around fatigue cracks in deep hyperboloidal-grooved specimens (0.20% C steel).

Specimen number	ρ^* and α	Stress, kg/mm²	Hardness of ferrite inside of 0.1 mm around crack			Hardness of ferrite outside of 0.1 mm around crack		
			Number of meas-urements	Mean hardness number	Standard deviation	Number of meas-urements	Mean hardness number	Standard deviation
0-12 (A)	ρ = 0.2 mm,	8.25	17	123	7.0	27	115	4.8
0-12 (B)			21	126	7.8	29	115	6.0
0-16	α = 4.62	8.5**	21	119	10 1	24	109	4.6
0-20 (A)	ρ = 0.5 mm,	8.5	16	120	6.9	29	110	6.1
0-20 (B)			10	124	9.0	27	109	6.7
0-21	α = 3.04	8.75**	30	118	10.3	22	108	5.2

* ρ; root radius, α; elastic stress concentration factor.
** The fatigue limit of the notched specimen.

4. Conclusions.

(1) As to the hardness changes in mild steels subjected to rotary bending stressing, the mean micro-hardness of the ferrite does not increase for stresses up to the fatigue limits of the steels, but do increase abruptly by about 7% for stresses beyond the fatigue limits; on the other hand, the mean micro-hardness of the pearlite does not change for stresses near the fatigue limits (below the lower yield points of the steels).

(2) From the results of micro-Vickers hardness tests on the ferrite around non propagating fatigue cracks in notched mild steel specimens, it will be expected that the magnitude of plastic (fatigued) region at the tip of the fatigue crack in carbon steels is several millimeter of hundredths (below 0.1 mm).

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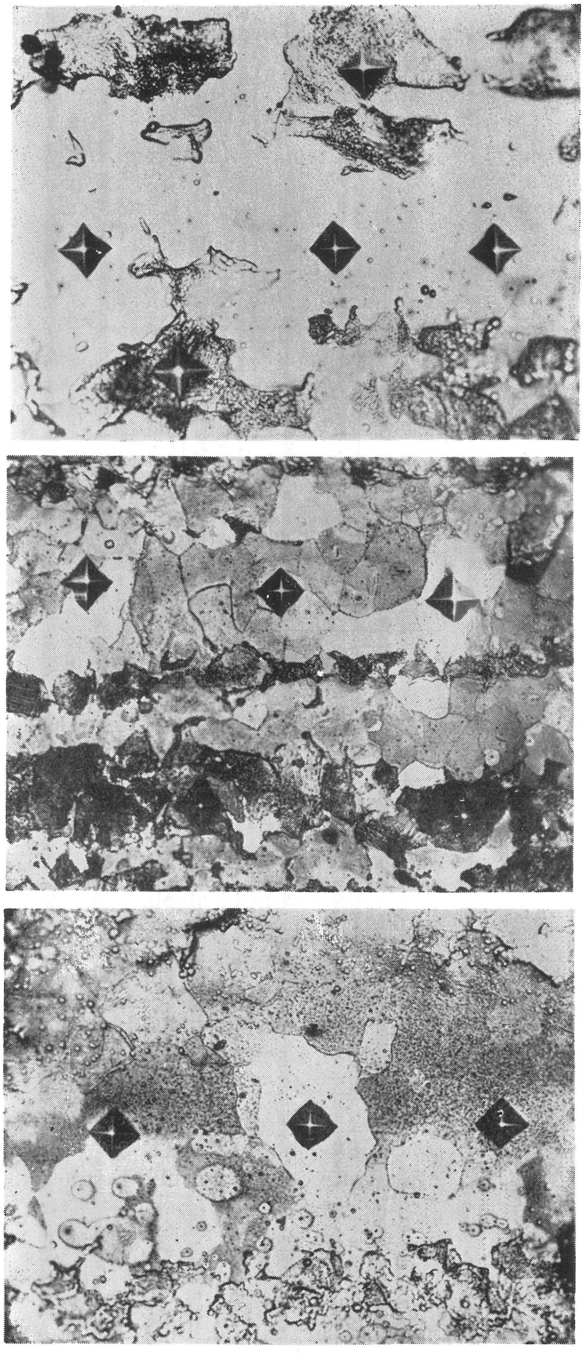


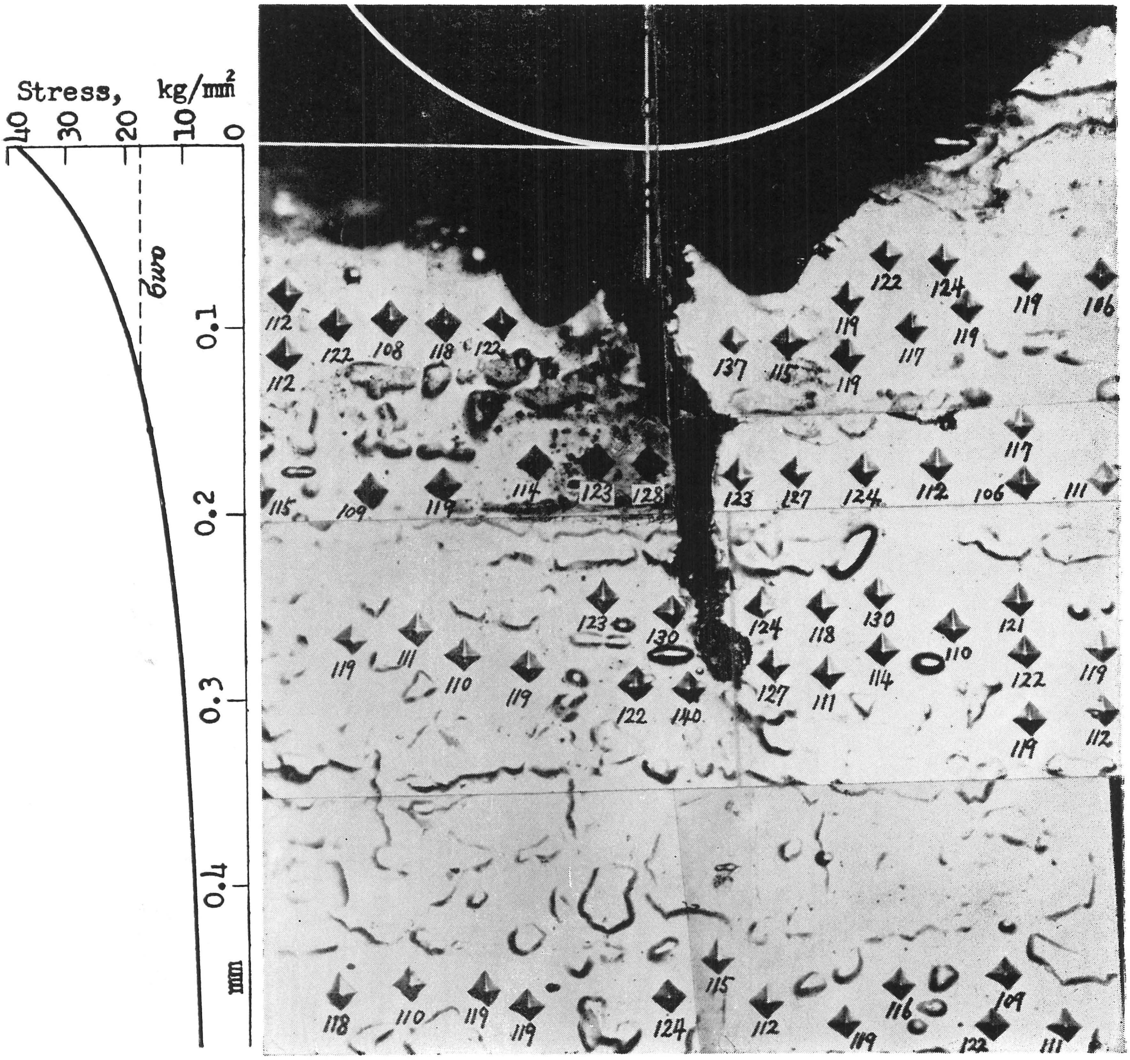
(a) 0.20% C steel.

(b) 0.23% C steel.

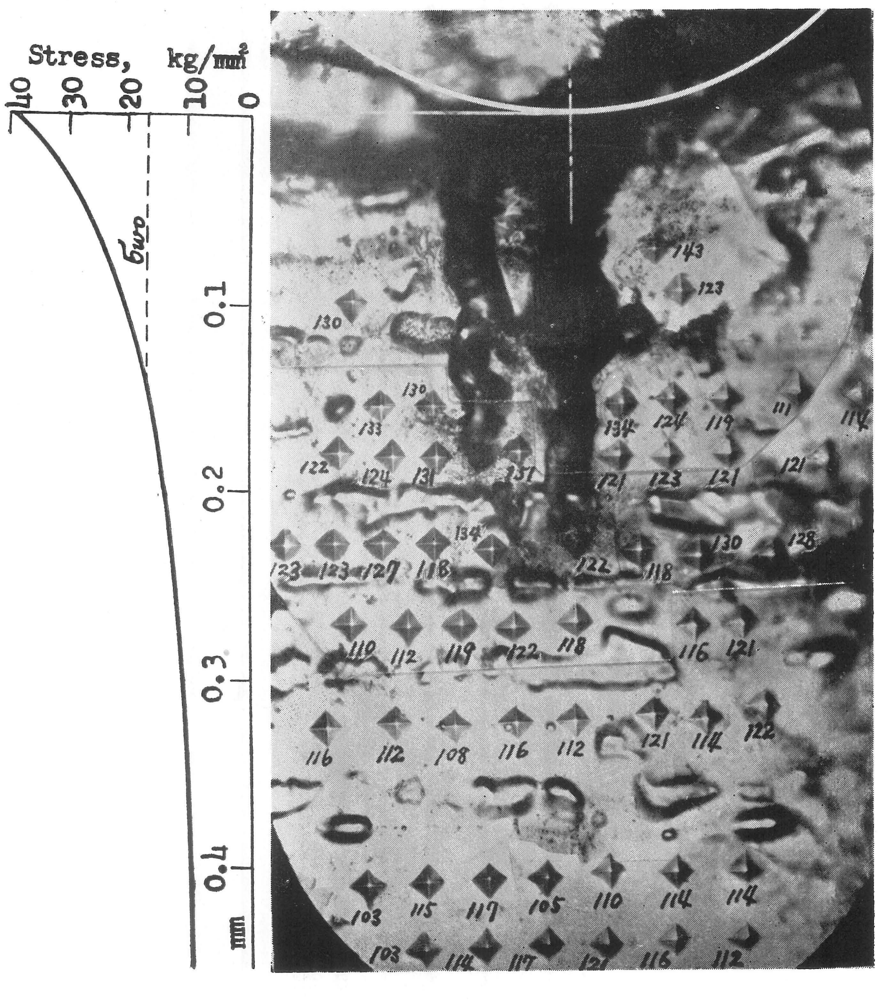
(c) 0.12% C steel.

Fig. 5. Photographs of indentations in the ferrite and pearlite grains of steels (× 340).

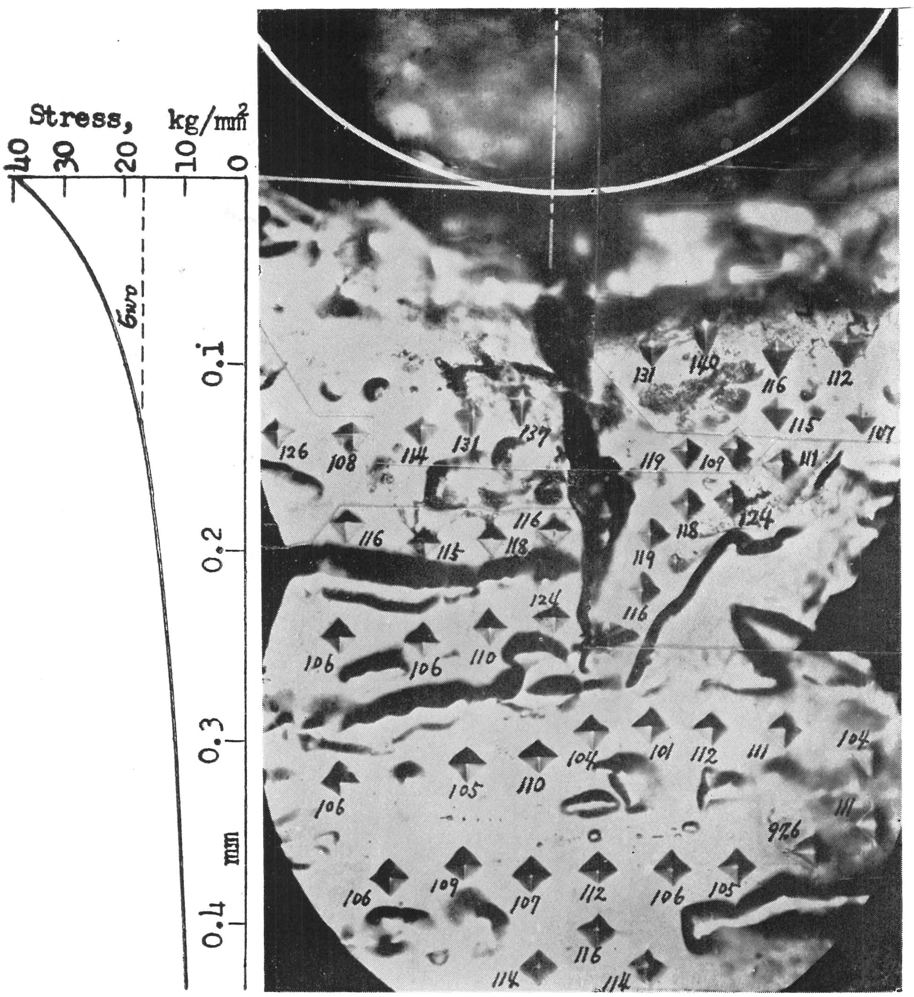
Fig. 6. Micro-hardness measurements for ferrite grains arouud non-propagating fatigue cracks in deep hyperboloidal-grooved specimens of 0.20% C steel (× 250).



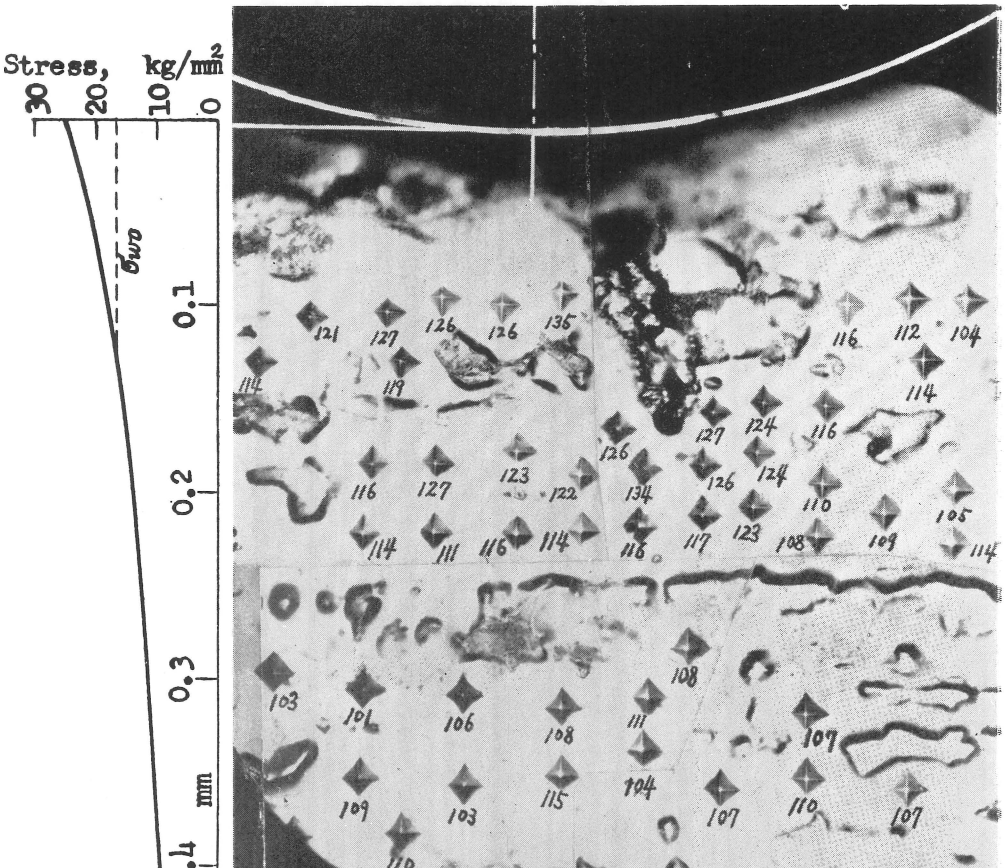
(a) Specimen number: 0–12 (A).



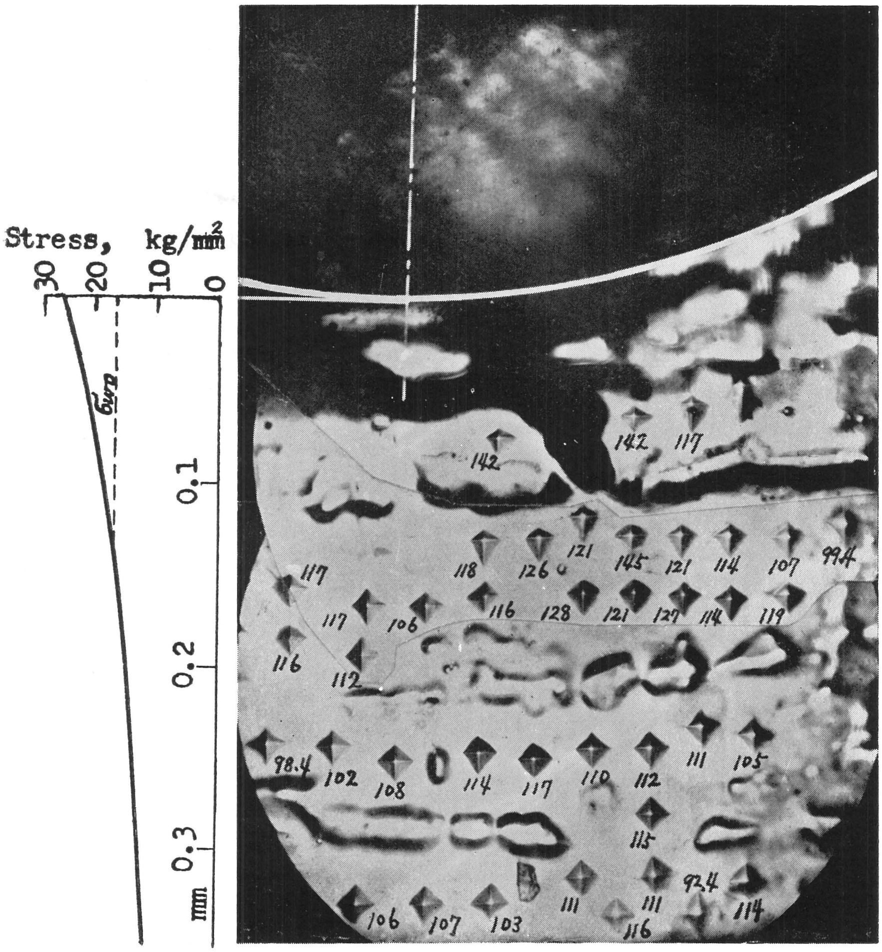
(b) Specimen number: 0–12 (B).



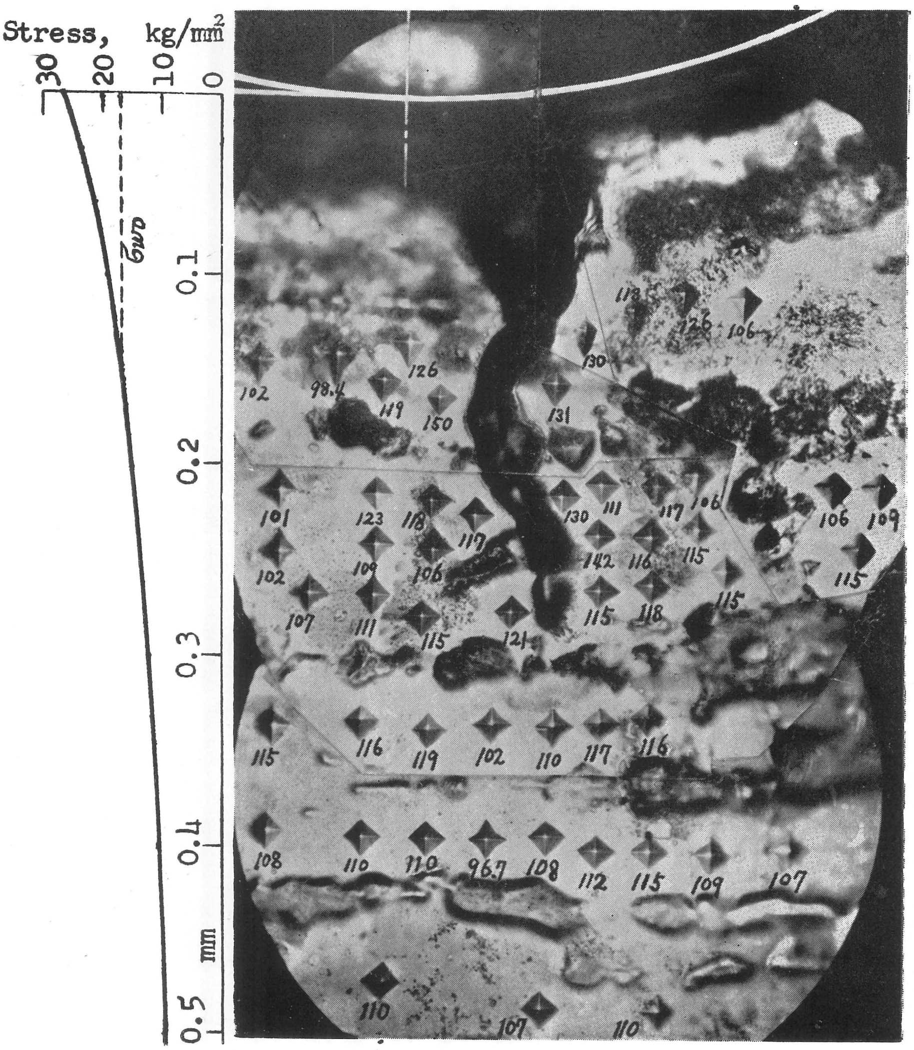
(c) Specimen number: 0–16.



(d) Specimen number: 0–20 (A).



(e) Specimen number: 0-20 (B).



(f) Specimen number: 0–21.