Submitted to Materials Science
and Engineering

LBL-2575
Preprint c.2

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August 1974

Prepared for the U. S. Atomic Energy Commission
under Contract W-7405-ENG-48

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ON HIGH FRACTURE TOUGHNESS OF COARSE-GRAINED AISI 4130 STEEL

G. Y. Lai*

Recent studies by Wood, et al.[1] at the University of California at Berkeley have shown that the fracture toughness of AISI 4130 steel can be greatly improved through austenitizing at temperatures higher than those normally employed. They observed that the plane strain fracture toughness, K_{IC}, was increased from 55 ksi-in.$^{1/2}$ (60.5 MN$\sqrt{m}$/m^2) when austenitized at 870°C and quenched in oil to 89 ksi-in.$^{1/2}$ (98 MN$\sqrt{m}$/m^2) when austenitized at 1200°C and quenched in oil, and further to 99 ksi-in.$^{1/2}$ (109 MN$\sqrt{m}$/m^2) when austenitized at 1200°C and quenched in iced brine and refrigerated in liquid nitrogen. However, the 0.2% yield strength obtained after the three different austenitizing treatments described above remained unchanged at about 200 ksi (1380 MN/m^2). Wood, et al. attributed this significant improvement in fracture toughness with increasing austenitizing temperature (a concomitant increase in austenite grain size from ASTM 7-8 to ASTM 0-1) to the elimination of undesirable austenite decomposition products, such as proeutectoid ferrite and upper bainite, during quenching. The as-quenched microstructure of this steel after austenitizing at 1200°C appeared to be completely martensitic structure when examined with an optical microscope. The extraordinarily high fracture toughness of the as-quenched martensitic structure having such a coarse prior austenitic

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grain size prompted the author to attempt a more definitive characterization of the microstructure.

The AISI 4130 steel had the following chemical composition in wt%: 0.31 carbon, 0.57 manganese, 0.85 chromium, 0.15 nickel, 0.18 molybdenum, 0.28 silicon, 0.21 copper, 0.009 sulfur and 0.008 phosphorous. The emphasis in this study was on those specimens that were austenitized at 1200°C for 1 hr and quenched in iced brine followed by liquid nitrogen refrigeration (1200°C IBQLN). Transmission electron microscopy was employed for microstructural characterization. Thin foils for examination were obtained directly from the fracture toughness specimens used in the previous investigation.[1]

The results of the present investigation confirmed the previous conclusions by Wood, et al.[1] viz, that austenitizing 4130 steel at 1200°C and quenching in iced brine virtually eliminated the formation of such undesirable austenite decomposition products as proeutectoid ferrite and upper bainite. The as-quenched structure became virtually a martensitic structure, as illustrated in Fig. 1. This figure shows the martensitic structure extending to the prior austenite grain boundary area, which is the most likely nucleation site for proeutectoid ferrite and upper bainite. Both proeutectoid ferrite and upper bainite were observed at prior austenite grain boundaries in 4130 specimens conventionally heat treated, viz, austenitized at 870°C and quenched in oil.[1]

The morphology of the martensite formed was dislocated laths; no twinned martensite plates were observed. Several investigators[2,3] have suggested that the presence of twinned martensite plates may be deleterious to toughness. It was further observed that autotempering had occurred in the as-quenched structure. The occurrence of autotempering in this steel was the result of its high M_s temperature--350°C for the specimen austenitized at 1200°C, as determined by Ericsson.[4] Both cementite and ε carbide were formed within martensite laths as a result of autotempering, as shown in Fig. 2. The ε carbide formed on $\{100\}_\alpha$ planes and the cementite on $\{110\}_\alpha$ planes, in agreement with the previous investigations.[2,5] No lath boundary carbides were observed in the as-quenched specimens. The occurrence of autotempering, which resulted in a uniform dispersion of either ε carbides or cementites, further added to the improvement in fracture toughness. Similar high strength and toughness in as-quenched, autotempered, Fe-5Mo-0.3C martensite have been reported.[6]

Also observed in the as-quenched coarse-grained structure was a significant amount of retained austenite dispersed as films between martensite laths, as shown in Figs. 3 and 4. Analysis of the diffraction pattern, as illustrated in Fig. 3(b), showed the orientation between austenite and martensite exhibiting the Kurdjumov-Sachs relationship, $\langle 111 \rangle_M \parallel \langle 110 \rangle_\gamma$. The presence of retained austenite films between martensite laths in the coarse-grained structure has also been reported in other low alloy steels austenitized at 1200°C.[2,3] It is known that plastic deformation is produced in the surrounding austenite when martensite forms and that this plastic deformation of austenite tends

to stabilize the austenite and to make it more difficult to transform to martensite.[7] The observed retained austenite remained stable even at liquid nitrogen temperatures--the as-quenched specimens having been refrigerated in liquid nitrogen prior to examination by transmission electron microscopy.

Austenite is known to be a tough phase that can relax local stress concentrations and delay the initiation of microcracks; also austenite films can effectively arrest growing microcracks. The thin austenite films could effectively limit the size of emissary cracks in front of the main crack.

It was concluded that for high fracture toughness at high strength levels, the formation of both proeutectoid ferrite and upper bainite has to be avoided. The desirable martensitic structure should consist of autotempered dislocated lath martensite with retained austenite films between the laths.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Professor E. R. Parker and Professor V. F. Zackay for their critical review of the manuscript and for their continued support during this investigation.

This research was performed partially under the auspices of the U. S. Atomic Energy Commission through the Inorganic Materials Research Division of the Lawrence Berkeley Laboratory, Contract No. W-4705-eng-48 and partially under the auspices of the Army Materials and Mechanics Research Center, Watertown, Ma., Contract No. DAAG46-73-C-0120 .

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FIGURE CAPTIONS

Fig. 1. Transmission electron micrograph of the as-quenched specimen austenitized at 1200°C (IBQLN) showing martensitic structure. The morphology of martensite is dislocated lath martensite. The prior austenite grain boundary is marked GB.

Fig. 2. Transmission electron micrographs of the as-quenched specimen austenitized at 1200°C (IBQLN) showing autotempered martensite with (a) and (b) both ε carbide and cementite, and (c) a Widmanstatten pattern of cementite.

Fig. 3. As-quenched lath martensite in the specimen austenitized at 1200°C (IBQLN): (a) bright field micrograph showing films of retained austenite (γ) between laths, (b) selected area diffraction pattern showing both austenite and martensite reflections (⟨110⟩ austenite reflections are illustrated by solid lines, ⟨111⟩ martensite reflections by broken lines).

Fig. 4. Transmission electron micrographs of the as-quenched specimen austenitized at 1200°C (IBQLN) showing films of retained austenite between martensite laths: (a) bright field image, and (b) dark field image of austenite reflection showing reversal contrast of retained austenite films.

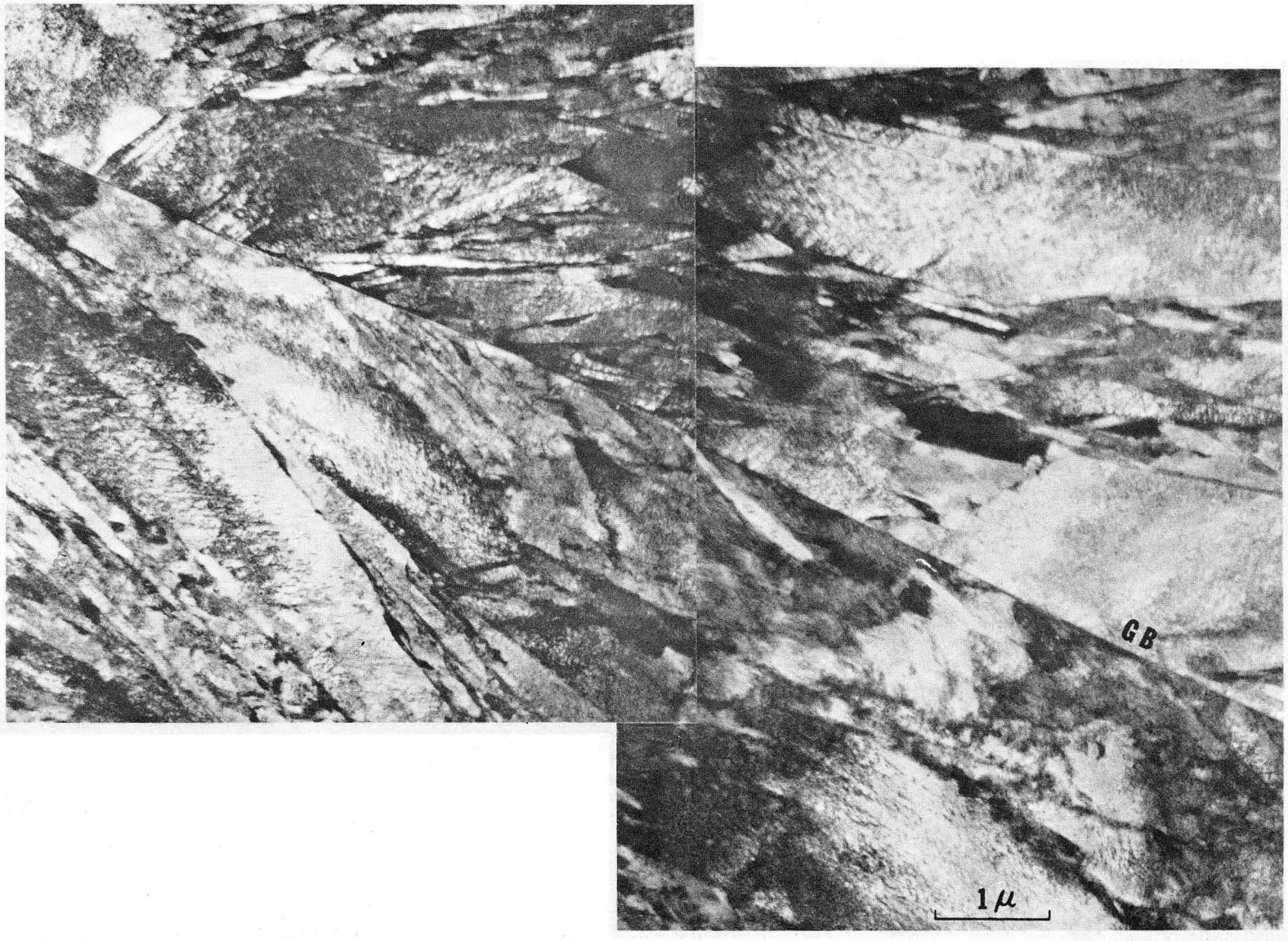

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Fig. 1

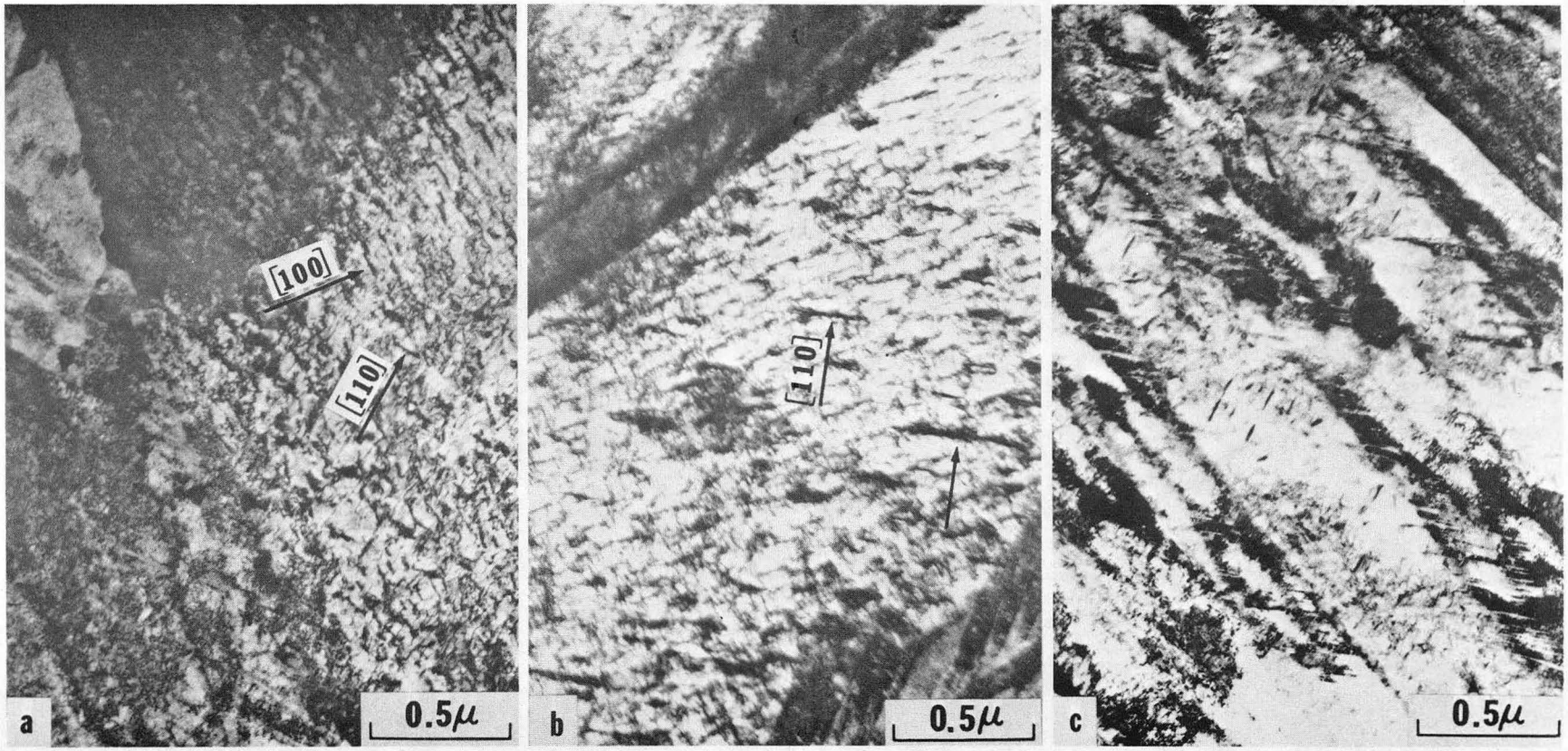

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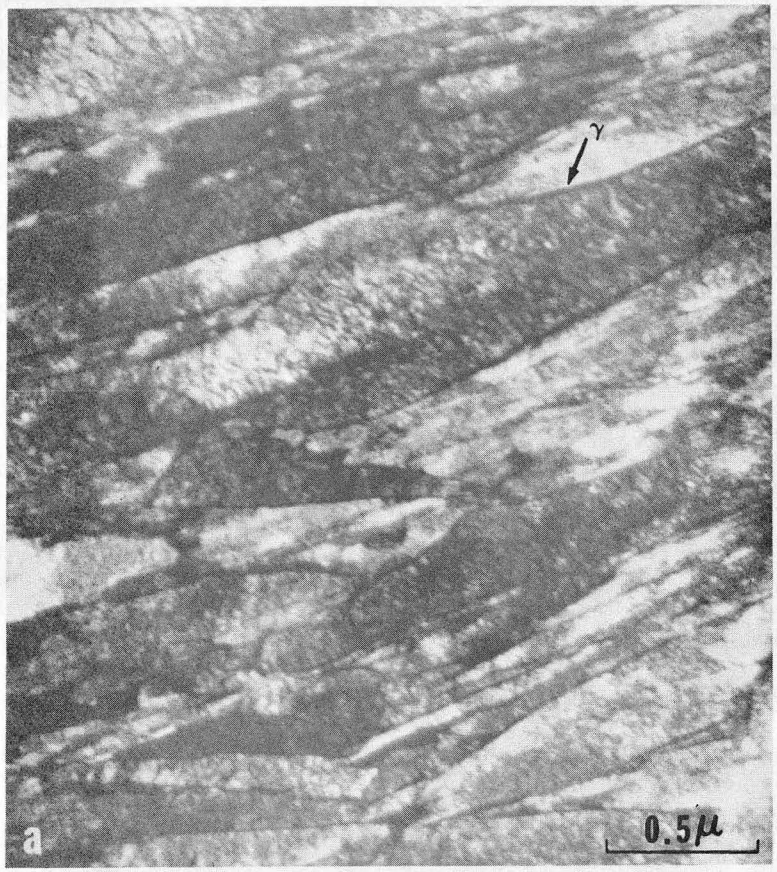
Fig. 2



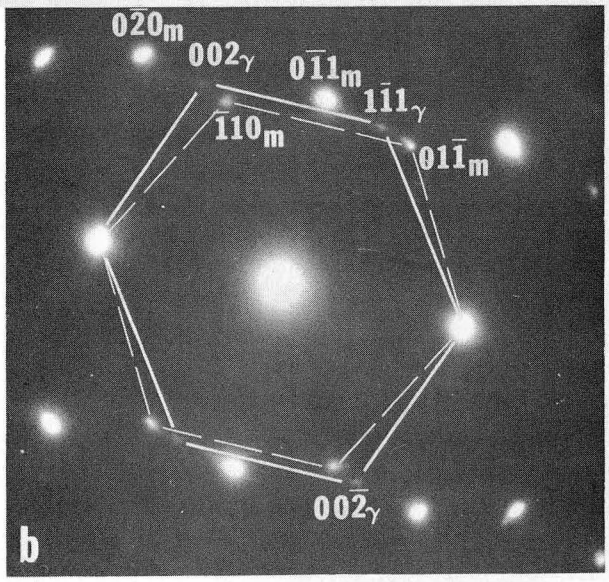


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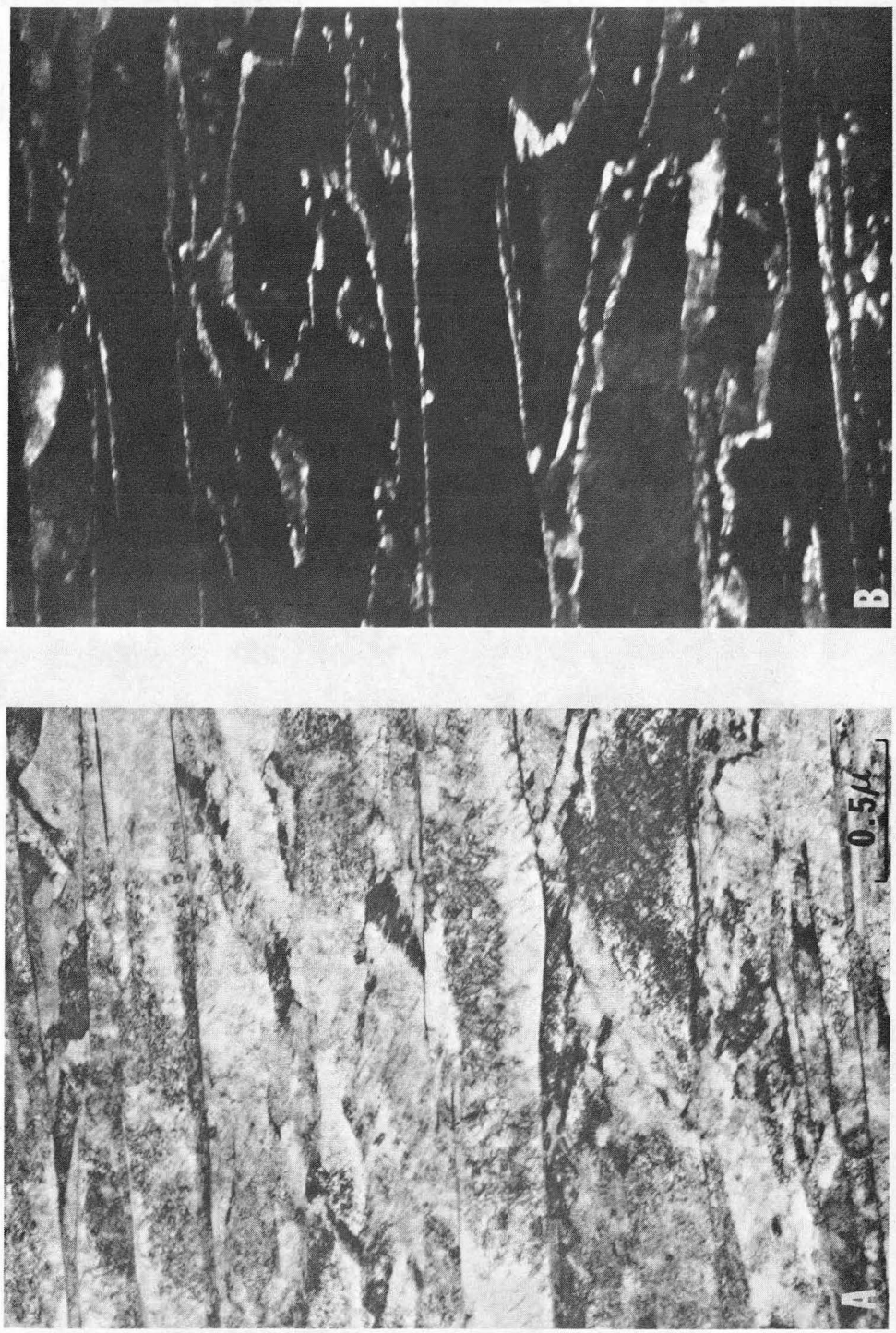
Fig. 3



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