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DISCLAIMER

INCREASING THE FRACTURE TOUGHNESS OF A MARAGING STEEL TYPE ALLOY

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Recent unpublished studies[1] have shown that the fracture toughness of a Fe-16Ni-1.5Ti maraging steel type alloy may be greatly improved by age hardening at higher temperatures (550°C-600°C) than those conventionally used (~ 450°C) for maraging steels. The purpose of this note is to describe the mechanisms believed to be responsible for the improved fracture toughness in specimens aged at the higher temperature.

In this alloy, austenite can form at all the aging temperatures investigated (450°C-600°C); whether or not it does form is strongly dependent on the time at temperature, as shown in Fig. 1, which shows the volume percent of austenite formed as a function of time of aging at 450, 500, 550 and 600°C. The data in Fig. 1 is for the isothermal rate of formation of austenite at the aging temperature. This is not necessarily the same as the rate of formation of retained austenite as measured at room temperature subsequent to aging. Thus, in the Fe-16Ni-1.5Ti alloy aged at 600°C there is no measureable <u>retained</u> austenite (measured by X-ray techniques) despite the large amount of austenite formed at temperature during aging. The formation of austenite in Fe-Ni-Ti alloys has been discussed by Jin[2] and Peters.[3] The data in Fig. 1 was obtained by a magnetic technique reported in detail by

Yuen.[4] It was observed that the austenite forms initially at the prior austenite and martensite lath boundaries.[1-3]

The precipitate in this alloy, hexagonal Ni_3Ti (DO_{24}), does not appear to precipitate in austenite. For example, in specimens aged at 650°C (at temperature at which a considerable amount of austenite is formed very rapidly) no precipitation is observed in the austenite; precipitation occurs only in the ferritic portions of the specimen. Furthermore, specimens which are fully austenitic may be cooled to temperatures anywhere in the range above the M_s (315°C for the Fe-16Ni-1.5Ti alloy) and held there without any precipitation being observed.[1]

As a consequence of the above, if austenite forms at a grain or lath boundary simultaneously with the precipitate, or before, the precipitation on the boundary appears to be largely inhibited by the presence of the austenite. The fracture toughness would improve in such a case because of the reduced amount of boundary precipitate and/or because of beneficial changes in the morphology of the boundary precipitate. In this model, the degree of interaction between the austenite and the boundary precipitate would be controlled by the relative rates of formation of the austenite and the precipitate.

Attempts to substantiate with direct evidence the validity of this hypothesis have proven to be difficult. Hot stage electron microscopy was unproductive due to the formation of a surface rather than a bulk precipitate--so that the structures obtained were very different from those observed on specimens aged in bulk and then examined. Thus it was not possible to observe directly the formation of the austenite on the boundary during aging. Furthermore, electron microscopy of specimens heat treated prior to examination did not clarify the problem for two reasons: (1) Austenite formed at the higher aging temperatures retransforms to ferrite upon cooling to room temperature and does not leave any observable evidence of its existence (the microstructures are highly dislocated so that evidence of the retransformation is obscured). (2) All of the specimens exhibit at least some boundary precipitation, and so it is not possible to clearly discern the difference between specimens aged at the various temperatures. For example, Fig. 2 shows boundary precipitation in specimens aged at 450°C and 550°C.

There is, however, some strong indirect evidence which suggests there is a beneficial interaction between austenite formation and boundary precipitation, and that this interaction is responsible for the reduced sensitivity to grain boundary cracking in specimens aged at the higher temperatures. Consider again Fig. 1, which shows both the percent austenite and the Rockwell C hardness (as a function of aging time). The hardness is used here as a measure of the "completeness" of the precipitation reaction. A comparison of the two sets of curves reveals that at the lower aging temperatures, for example 500°C, austenite has just begun to form when the peak hardness is reached at 10^3 secs. Conversely, at the highest aging temperature, 600°C, austenite formation and Ni_3Ti precipitation are occurring simultaneously. For example, at 600°C the hardness is R_c 30 at an aging time of 35 secs and at this time there is approximately 10% austenite. Thus there is a correlation between the relative rates of formation of austenite and precipitate with the development of the best fracture toughness--

namely that when the formation of austenite and of Ni_3Ti occur simultaneously, i.e., at 600°C, the fracture toughness improves. The improvement of fracture toughness with increased aging temperature is shown in Table I. It should be noted that the improvement in fracture toughness occurs at a constant yield strength level (~200 ksi or ~1,379 MPa).

It will be noted from Table I that the toughness of specimens aged at 600°C is considerably better than for specimens aged at 550°C, even though in both cases austenite and precipitate formation (Fig. 1) are occurring approximately simultaneously. This suggests that there is a critical balance between the rate of formation of austenite and of precipitate at the grain or lath boundaries, and that at 500°C a deleterious amount of boundary precipitation has taken place prior to the onset of austenite formation. Evidence in support of this view is illustrated in Fig. 3, which shows SEM fractographs of the fatigue cracked regions of fracture toughness specimens aged at 550°C and 600°C. The 550°C specimen shows considerably more grain boundary cracking than does the 600°C specimen, as demonstrated by the lesser amount of smooth, faceted areas in the 600°C micrograph. This indicates that there was more boundary precipitation in the 550°C specimen, and is consistent with the lower fracture toughness. In this regard it should be noted that the fracture toughness of 550°C aged specimens is greater, as shown by the CVN (Table I), than that of the 450°C aged specimens; so there is some beneficial interaction occurring during aging at 550°C, as Fig. 1 would suggest there might be.

In conclusion, a correlation is observed between aging temperature and fracture toughness, with the higher aging temperatures giving improved fracture toughness. It is shown that the higher aging temperatures improved the toughness by reducing the tendency for grain boundary cracking, i.e., by reducing the amount of and/or by changing the morphology of the grain boundary precipitate. Finally, it is suggested that there is an interaction between the formation of austenite and the formation of precipitate on the prior austenite and the lath boundaries, and that if austenite forms sufficiently early in the aging process boundary precipitation may be largely inhibited. This interaction is believed to account for the improved toughness at the higher aging temperatures. This suggestion is supported by indirect evidence consisting largely of the relationship between the rate of formation of austenite and the rate of formation Ni_3Ti as a function of aging temperature.

ACKNOWLEDGEMENT

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2. Sungho Jin, Ph. D. Thesis, University of California, Berkeley, LBL-2789, 1974.
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Table I. Fracture toughness for various aging temperatures.

Alloy (wt %)	Aging Temp.	R_c Hardness (σy ~1,379 MPa)	K_{IC} $MPa \cdot m^{1/2}$ (23°C)	CVN N·M (23°C)
Fe-16Ni-1.5Ti (vacuum induction melted)	600°C	43	~125	37
	550°C	43	~ 55	19
	450°C	43	-	4

200 ksi = 1,379 MPa

1 ksi$\sqrt{in.}$ = 1.1 MPa $m^{1/2}$

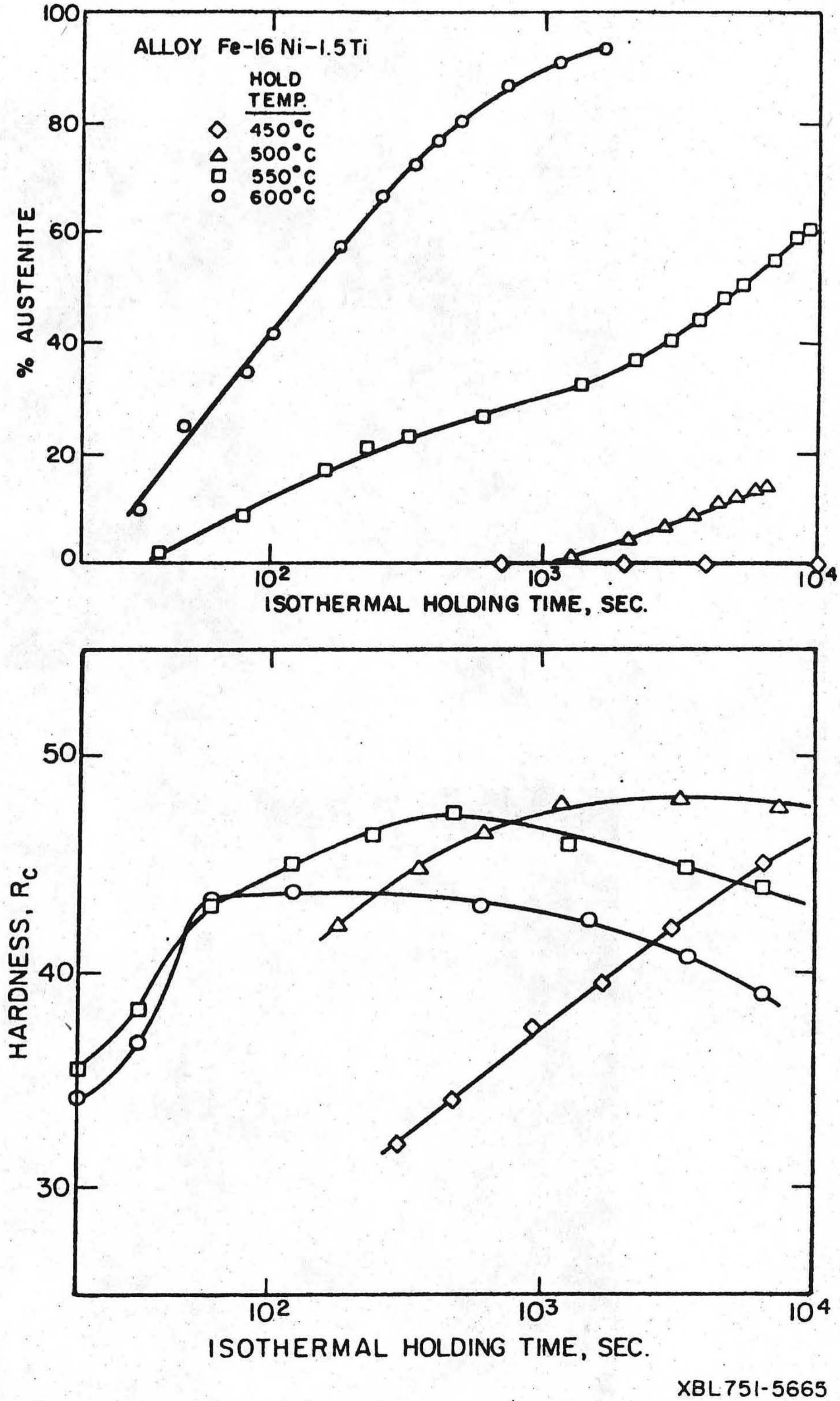
1 ft-lb = 1.36 joules

FIGURE CAPTIONS

Fig. 1. The volume percent austenite and the Rockwell "C" hardness of the 16Ni-1.5Ti alloy as a function of aging time.

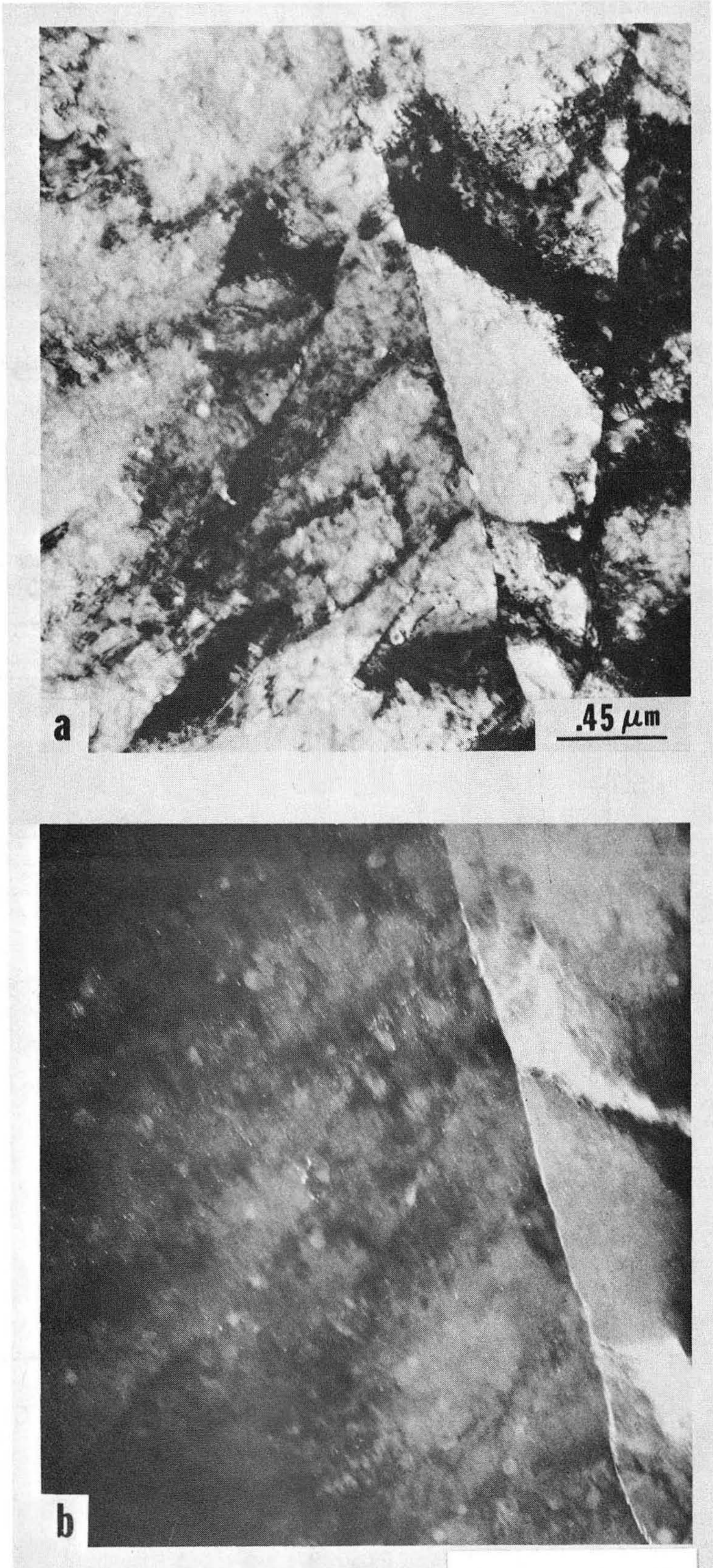
Fig. 2. Bright field (a) and dark field (b) transmission electron micrographs showing grain boundary precipitation in the 16Ni-1.5Ti alloy. (A) Aged at 450°C. (B) Aged at 550°C.

Fig. 3. SEM fractographs of fatigue cracked portions of CTS specimens aged at (a) 550°C and (b) 600°C. The 600°C specimen shows considerably less grain boundary fracture than does the 550°C specimen. Both micrographs show representative areas.



ALLOY Fe-16 Ni-1.5 Ti
HOLD TEMP.
450°C
500°C
550°C
600°C
% AUSTENITE
0
20
40
60
80
100
10^2
10^3
10^4
ISOTHERMAL HOLDING TIME, SEC.
HARDNESS, R_c
30
40
50
10^2
10^3
10^4
ISOTHERMAL HOLDING TIME, SEC.
XBL 751-5665

Fig. 1



XBB 753-2205

Fig. 2A

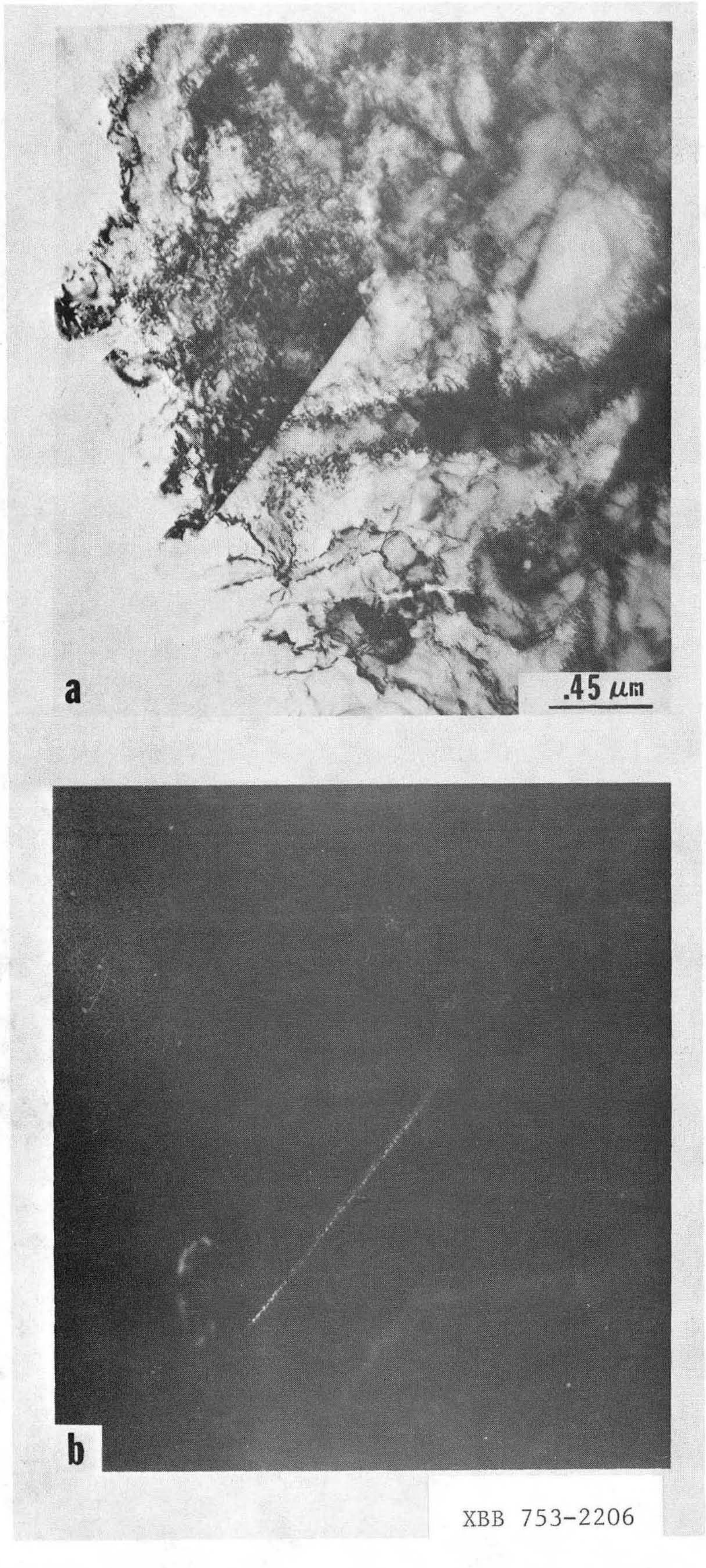


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Fig. 2B

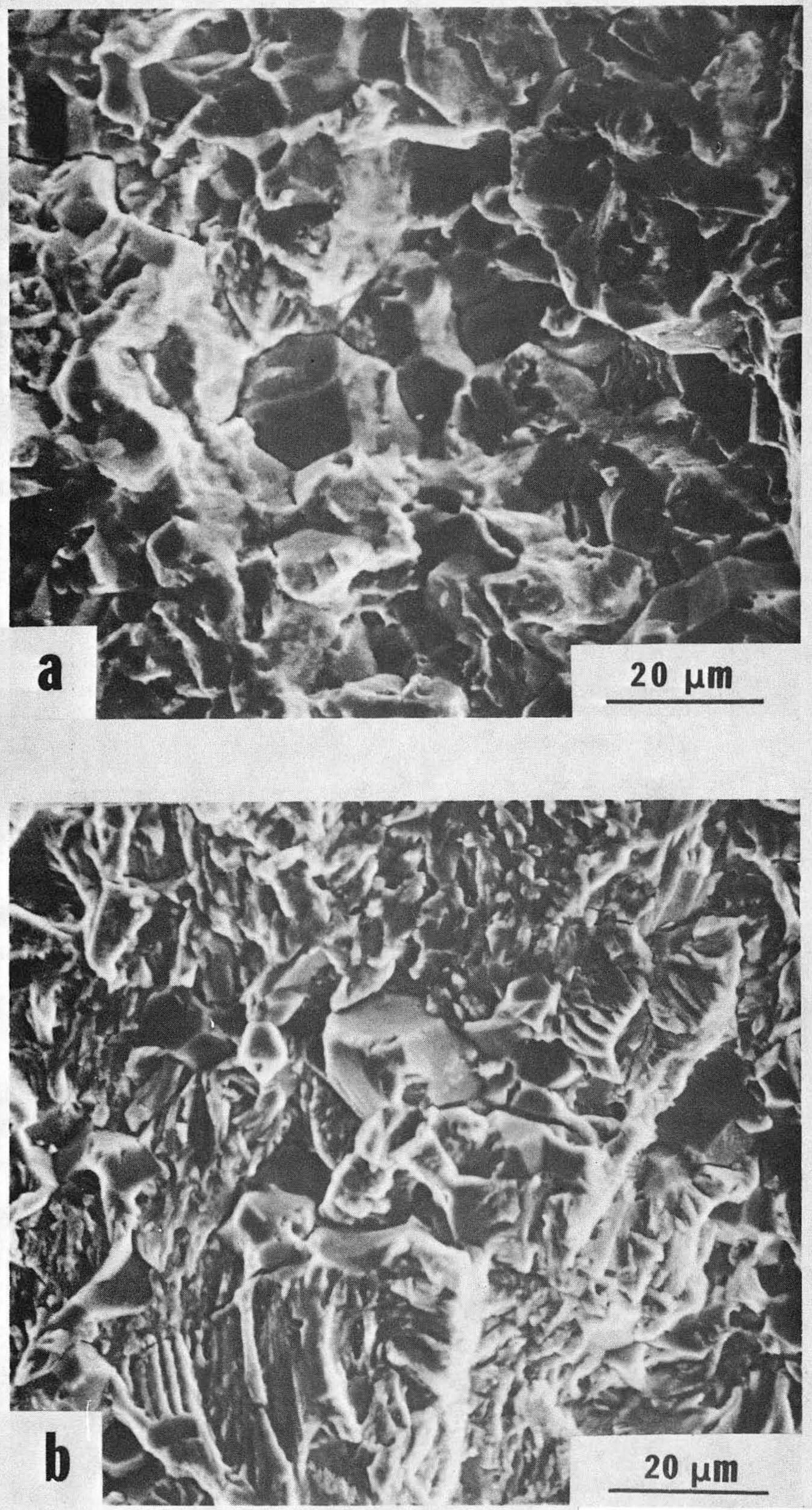

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Fig. 3