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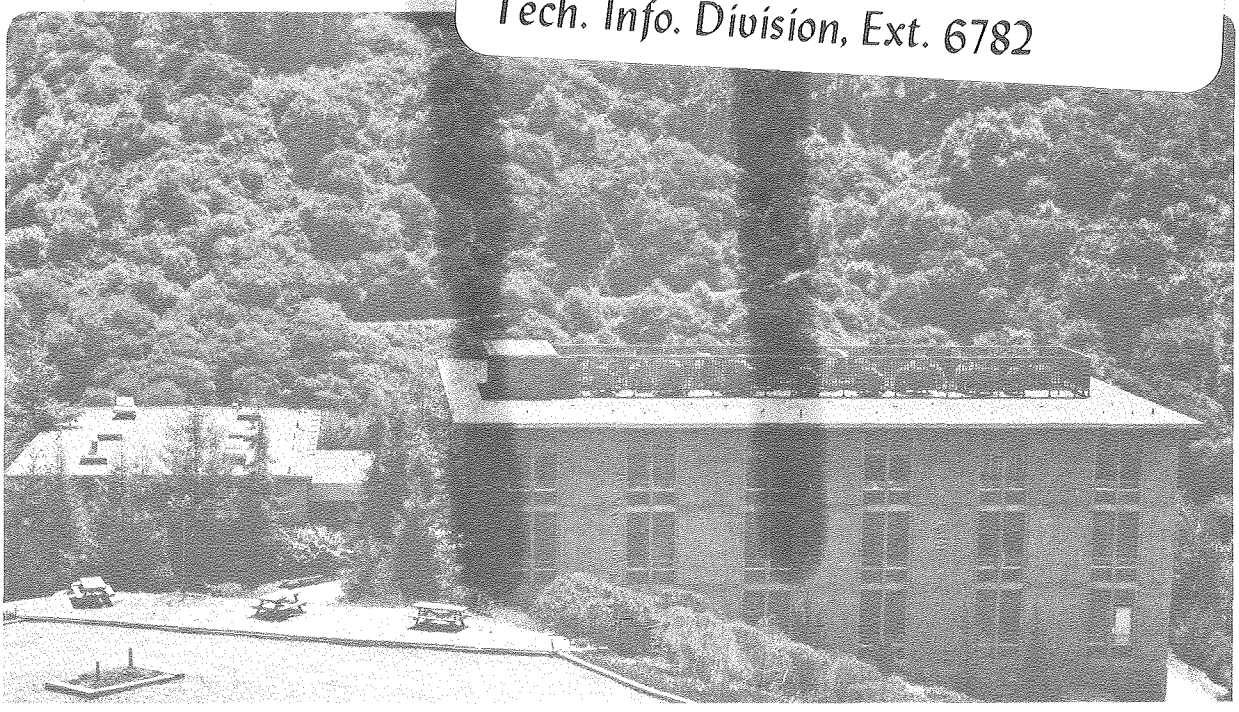

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MICROSTRUCTURE AND PROPERTIES OF DUAL PHASE STEELS CONTAINING FINE PRECIPITATES[+]

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ABSTRACT

Very fine particles (carbides or carbonitrides) of the order of 20 Å were extensively examined in the ferrite regions of dual-phase steels subjected to intercritical annealing followed by fast quenching to room temperature. These particles are probably formed during quenching after intercritical annealing. The driving force for the precipitation reaction may arise from the supersaturation of carbon (or nitrogen) in the ferrite phase. These precipitates in certain alloy compositions cause a deviation from the generally observed two phase mixture rule in that the strength of the dual-phase steels having a higher volume fraction of martensite is lower than that having a lower volume fraction of martensite. Thus, the influence of such precipitates must be considered in the structure-property relations of dual-phase steels when fast quenching is employed after intercritical annealing.

INTRODUCTION

Significant advances have been made in the past several years in our understanding of structure-property relations in intercritically annealed dual-phase steels. Many of the results are published in two recent conference proceedings[1,2]. Among the variables which may be important in influencing these relationships are the volume fraction of martensite, size and distribution of martensite, properties of the constituent phases,

retained austenite, and fine precipitation in the ferrite.

It is only very recently that very fine carbides (or carbonitrides) of the order of 20 Å have been observed in the ferrite region of as-quenched dual-phase steels[3,4]. Important consequences of this precipitation on the mechanical behavior of dual-phase steels was first reported by Thomas and Koo[3]. This paper presents recent developments on the microstructure and mechanical properties of various dual-phase steels containing fine precipitates. Emphasis will be placed on the origin and characteristics of the particles, and the influence of alloying elements on the formation and morphology of the particles.

FORMATION OF FINE PRECIPITATES

By holding in the ($\alpha+\gamma$) region, the steel will consist of low carbon ferrite (α) and higher carbon austenite (γ). Although the carbon content in the ferrite is negligibly small compared to that in the austenite, it could be significant enough to cause precipitation in the ferrite. This can be seen from the Fe-rich portion of the Fe-C phase diagram[5], which clearly indicates that the solubility of carbon in ferrite at the intercritical annealing temperature is many times ($\sim$100 times at about 50% volume fraction of ferrite) greater than that at room temperature. This situation is enhanced when a ferrite stabilizing element, e.g., Si is present in the steel as an alloying element.

Thus, quenching from the intercritical annealing temperature creates a large supersaturation of interstitial carbon which can provide a driving force for carbide precipitation in the ferrite. The quenching rate is critical in the formation of the precipitates since, if slowly cooled from the ($\alpha+\gamma$) region, the supersaturation of carbon in the ferrite

will be reduced or eliminated due to the diffusion of carbon into the shrinking austenite.

It is also important to note from the Fe-C phase diagram that, in the $(\alpha+\gamma)$ field, the solubility of carbon in ferrite decreases as the intercritical annealing temperature increases. This means that the carbon supersaturation level at room temperature increases as the intercritical annealing temperature decreases, or alternatively as the volume fraction of martensite decreases in the final quenched product. As a result, it should be expected that the higher the volume fraction of martensite, the lower the density of precipitates in the ferrite region.

The mechanism for this precipitate formation will be discussed in a later section.

ALLOY SYSTEMS STUDIED

The microstructures of dual-phase steels which were extensively investigated with respect to the precipitation phenomena are described in this section. The essential part of the dual-phase heat treatment is that after intercritical annealing all the alloys were subjected to either a water quench (WQ) or an iced brine quench (IBQ) unless otherwise specified.

Fe/Nb/0.1C

The chemical composition of the steel containing Nb was Fe/0.4 Si/0.04 Nb/0.1 C. The specimens were intercritically annealed at 800 to 850°C which correspond to a volume fraction of 20% and 40% austenite (martensite after quenching), respectively. At each temperature, the specimens were held for 10 minutes in a vertical tube furnace under an

an argon atmosphere.

The optical microstructures observed in the Nb containing dual-phase steels are shown in Figure 1.

Transmission electron microscope examination of the structure revealed extensive precipitation in the ferrite region, as shown in Fig. 2. Figure 2(a) is a bright field image showing extremely fine particles of the order of $\sim$10 Å wide and $\sim$50 Å long in the ferrite region of Figure 1(a) having 20% martensite. These particles are visible by strain contrast only when favorable diffracting conditions are met. Another ferrite region of interest is shown in Figure 2(b). It can be noted from the figures that the particles show dislocation loop contrast which is typical of coherent precipitates, and that there are precipitate free zones near dislocations and the α/α grain boundary.

A slow cooling experiment was conducted in an attempt to determine if the particles are formed during intercritical annealing or if they are undissolved particles. After annealing at 800°C, the specimens were forced air cooled to room temperature. The resultant TEM micrograph is illustrated in Figure 3, where the ferrite regions are relatively clean and are not associated with extensive precipitation. Thus, this result rules out the possibility of undissolved particles or of particle formation during intercritical annealing, and suggests that they may be formed during quenching to room temperature. A further discussion will follow in a later section.

The morphology of the particles in the ferrite region of Figure 1(b) having 40% martensite was very similar to that shown in Figures 2(a) and 2(b), except for a definite decrease in the density of precipitation as

expected. The quantitative measurements of the particle density in the two specimens, together with the habit plane determination of the particles, will be described in the paper by Hoel and Thomas in this volume. At present, the crystal structure and chemical composition of the precipitates are not clearly known. However, all the experimental evidence to date seems to indicate that they are ε carbide, cementite, or carbonitrides.

The room temperature tensile properties of the two specimens (Figure 1(a) and 1(b)) are summarized in Table 1 and the stress-strain curves are plotted in Figure 4. It is interesting to note from the data that the strength of the 850°C WQ specimen having 40% martensite is lower than that of the 800°C WQ specimen having 20% martensite. The apparent relaxation of the law of mixtures observed in the Nb containing steels can be explained based on the varying density of precipitation in the ferrite as the volume fraction of martensite varies. The quantitative treatment on this point will appear in the paper by Hoel and Thomas.

Fe/N/0.1C

The alloying addition of V was studied to determine the role of V on the structure-property relationship in dual-phase steels. The chemical compositions of the base steel and the V modified steel were Fe/1.15 Mn/0.6 Si/0.12C and Fe/1.22 Mn/0.6 Si/0.12 V/0.1 C, respectively. The specimens were intercritically annealed at 800°C for 10 minutes followed by an IBQ. The TEM micrographs taken from the base steel after the 800°C/IBQ treatment are shown in Figure 5. Figure 5(a) illustrates the morphology of the martensite/ferrite interface and its vicinity. The martensite consists of predominantly dislocated laths and the ferrite region near the interface is heavily dislocated. These features represent

the typical microstructure of dual-phase steels as reported by many investigators[1,2]. The other transformation products of austenite, e.g., bainite and pearlite were not observed due to the fast quenching rate. The "retained ferrite", the ferrite regions retained during the intercritical annealing treatment[6], showed a relatively low density of fine precipitation (Figure 5(b)).

The microstructures observed in the V modified steel after the 800°C IBQ treatment were similar to those of the base steel as described above, except for discontinuous precipitation in the "new" ferrite near the martensite/ferrite boundaries, and for an increased density of fine precipitation in the retained ferrite. The morphology of the discontinuous carbide precipitation is shown in Figure 6(a). The precise identification of the carbides was not attempted in this study, but they are presumably cementite[6,7] or a vanadium carbide[8,9]. This type of structure is similar to the new eutectoid transformation products observed in the isothermal decomposition of austenite in steels containing strong carbide forming elements.

In the retained ferrite regions, very fine precipitates were extensively observed, as shown in Figure 6(b). The density was higher in this alloy than that in the base steel, and this indicates that V enhances the formation of such precipitates. The contrast characteristics of the particles appear to be identical to those observed in the Nb containing steel.

As described above, V modifies the morphology of the carbides in the base steel. Nevertheless, the modified microstructures did not result in improved mechanical properties for the steel composition and the heat treatment considered. Further experiments have shown that the V addition

to the base steel was not beneficial even for air cooled or forced air cooled material after intercritical annealing.

Other Steels

Similar fine precipitation morphologies were observed in the ferrite regions of dual-phase steels containing Mo and Al[4]. This precipitation is not limited to steels bearing carbide or nitride forming elements. 1010 steels[10] and Fe/1.5 Si/0.1C steel[11] also revealed extensive precipitation. In all cases, the characteristic features of the particles were identical. The only experimentally observable effect of the alloying elements was the increase in the density of precipitation with alloying additions, especially with Nb and V.

DISCUSSION

It is clear from the preceding experimental results that the precipitation phenomenon found in the ferrite of steels fast quenched after intercritical annealing is a general observation rather than a random occurrence. The presence of carbide forming elements in dual-phase steels can enhance precipitation, but it is not required to form the precipitates. A question arises as to when are the precipitates formed. The possibility that they form during intercritical annealing or that they are undissolved particles present in the starting microstructure is ruled out by the following experimental evidence. The slowly cooled specimens after intercritical annealing do not have the fine particles. Secondly, a dual-phase 1010 steel which does not contain carbide forming elements revealed extensive precipitation[10].

A possibility exists that natural aging or thin foil surface preparation effects may account for the precipitation. To check for

natural aging, the microstructures were examined immediately after heat treatment, and after several prolonged natural aging treatments. The results show the same size and morphology of the particles in all cases, which excludes the possibility of room temperature precipitation. Likewise, thin foil surface effects were eliminated by sputtering the thin foil surface and also using different electropolishing solutions. At present, therefore, the most plausible explanation is the formation of the particles during quenching to room temperature. This process may be similar in nature autotempering observed in steels with high M_S temperatures.

The presence of precipitates does not always give rise to a violation of the two phase mixture rule. Violation did occur in the alloys containing Nb, Mo and Al but did not occur in 1010 steel[10], Fe/Si/C[12], and Fe/Cr/C steels[12]. The results suggest that, although the image characteristics of the particles were identical in all the alloys studied, the elements Nb, Mo and Al apparently influence the particle properties in such a way that they act as more effective barriers to dislocation motion. In this case, dispersion strengthening becomes significant. Thus, the strength of ferrite with a higher volume fraction of martensite is lower than that with a lower volume fraction of martensite because of the change in precipitate density. This situation is responsible for the relaxation of generally observed law of mixtures.

CONCLUSIONS

A very fine dispersion of coherent particles (carbides or carbonitrides) of the order of 20 Å were observed in the ferrite region of

of dual-phase steels subjected to intercritical annealing followed by fast quenching to room temperature. These particles probably form during quenching after intercritical annealing. The driving force for the precipitation reaction may arise from the supersaturation of carbon (or nitrogen) in the ferrite phase.

The particles were observed in all the steels we have thus far investigated regardless of alloy compositions. These precipitates in certain alloy compositions, especially those containing Nb caused a relaxation of the two phase mixture rule, i.e., the strength of the dual-phase steels having a higher volume fraction of martensite was lower than that of a lower volume fraction of martensite.

Thus, the influence of such precipitates must be considered in the structure-property relations of dual-phase steels when the fast quenching is employed after intercritical annealing.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Fig. 1. Optical micrographs showing dual-phase microstructures in the Fe/0.4 Si/0.04 Nb/0.1C steel (a) annealed at 800°C for 10 minutes and water quenched, (b) annealed at 850°C for 10 minutes and water quenched, 2% nital etch.

Fig. 2. Transmission electron micrographs showing very fine precipitates in the ferrite regions of Figure 1(a).

Fig. 3. Transmission electron micrograph showing the ferrite regions in the Nb containing steel. Intercritically annealed at 800°C and subsequently forced air cooled.

Fig. 4. Stress-strain curves for the Nb dual-phase steels. Forced air cooled (FAC) specimens are also included in the plot.

Fig. 5. Transmission electron micrographs showing (a) martensite and ferrite regions, and (b) fine particles in the retained ferrite.

Fig. 6. Transmission electron micrographs showing (a) aligned, discontinuous carbides in the vicinity of martensite/ferrite interfaces, and (b) the fine precipitation in the retained ferrite.

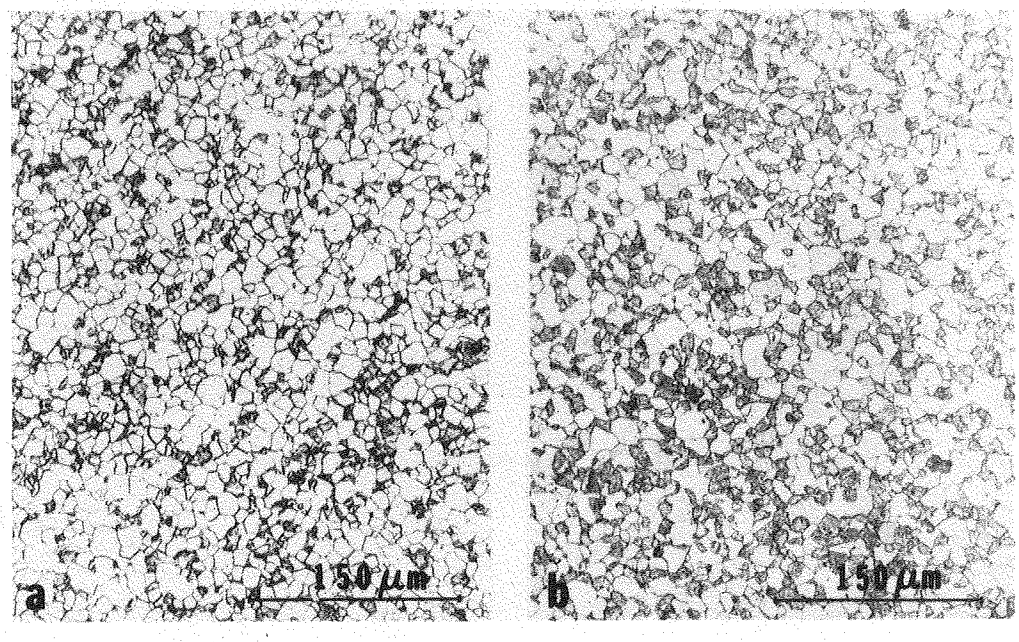

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Fig. 1

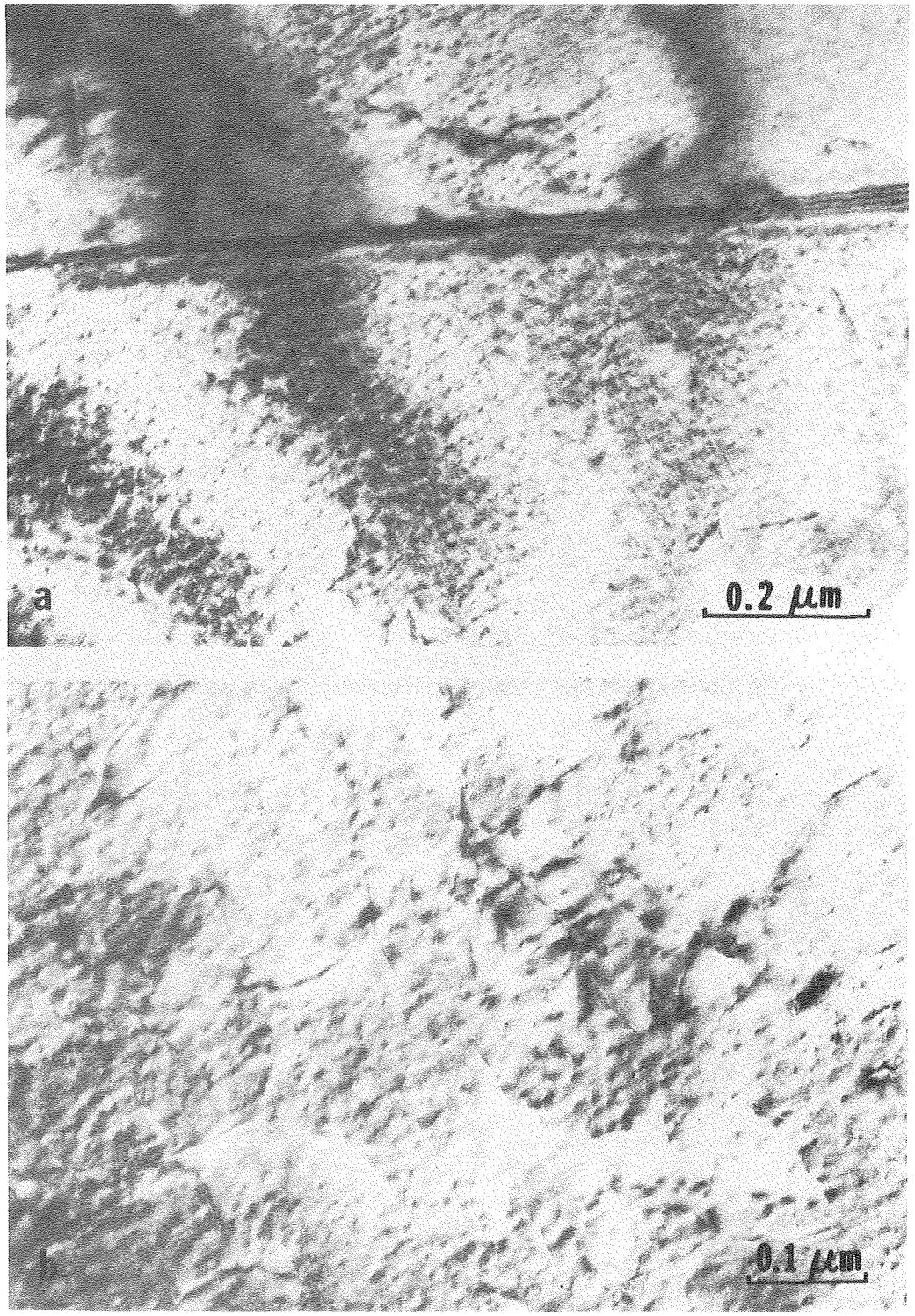

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Fig. 2

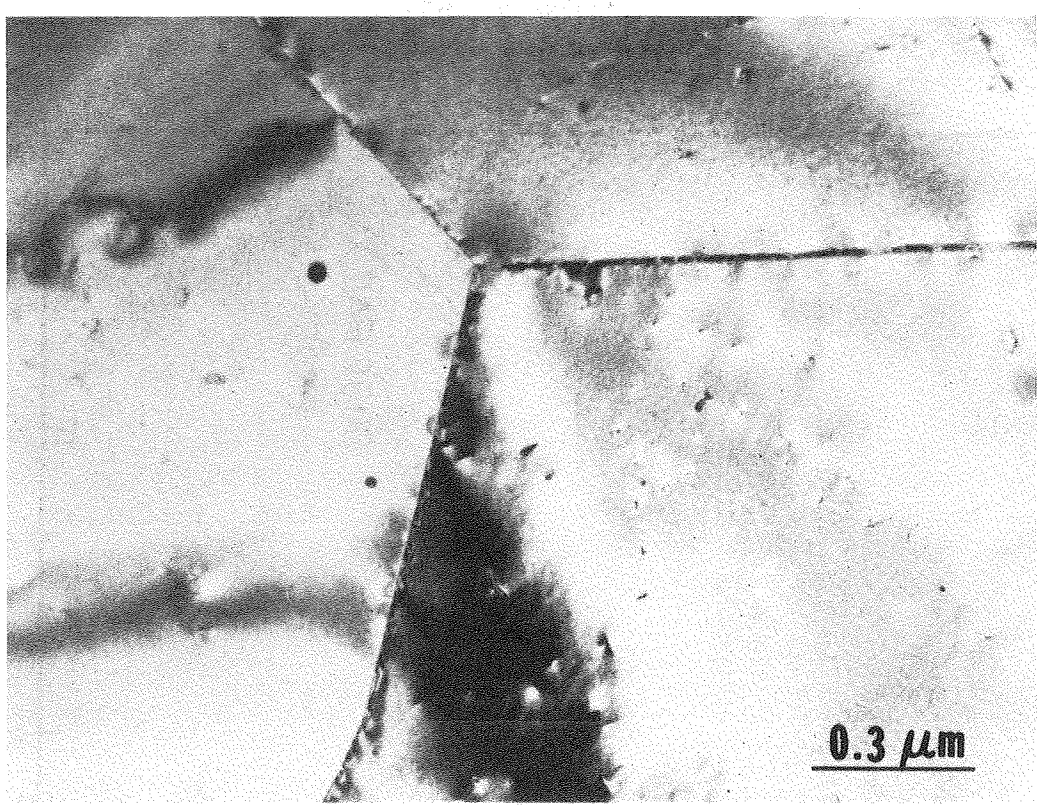

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Fig. 3

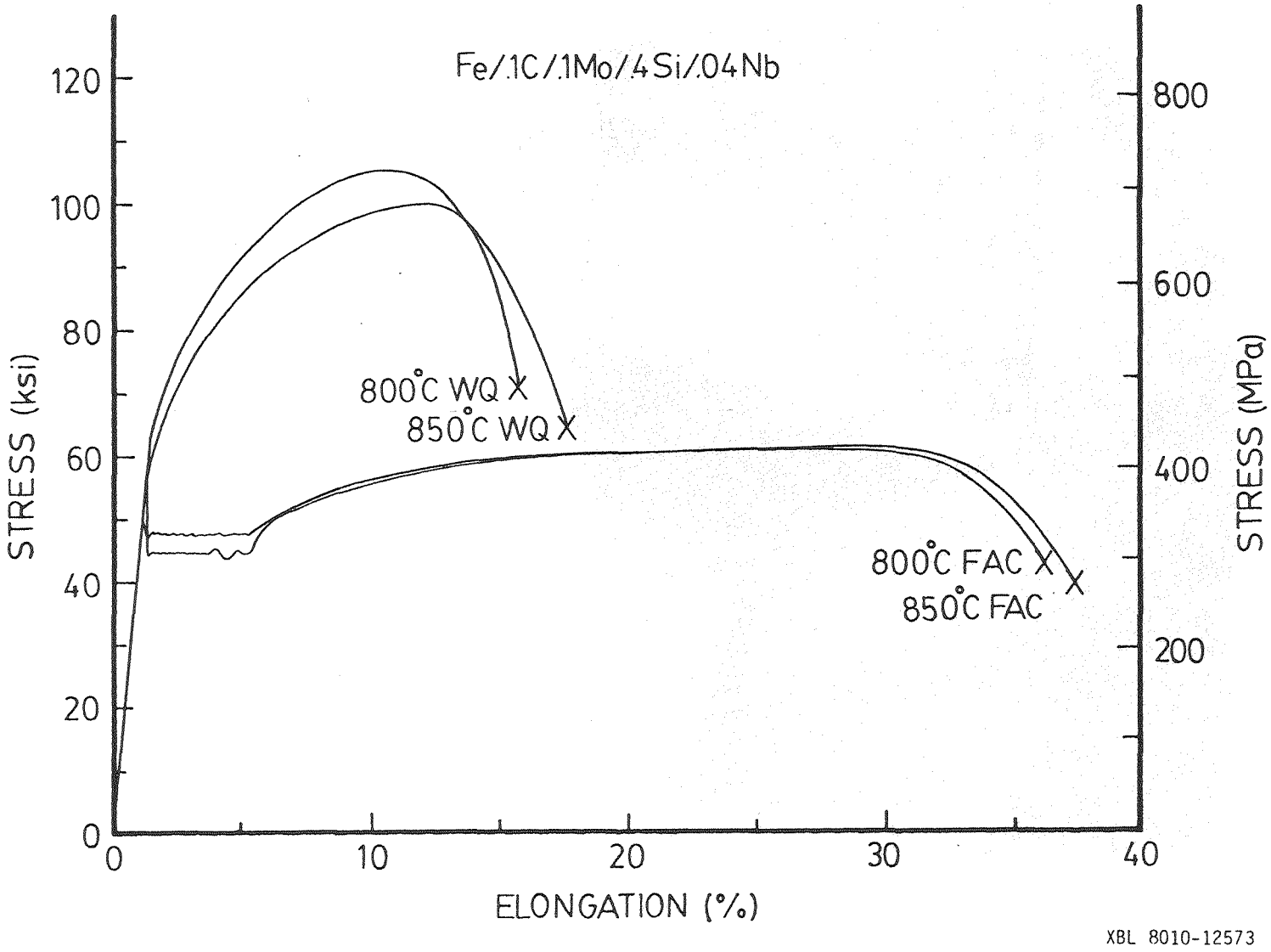

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Fig. 4

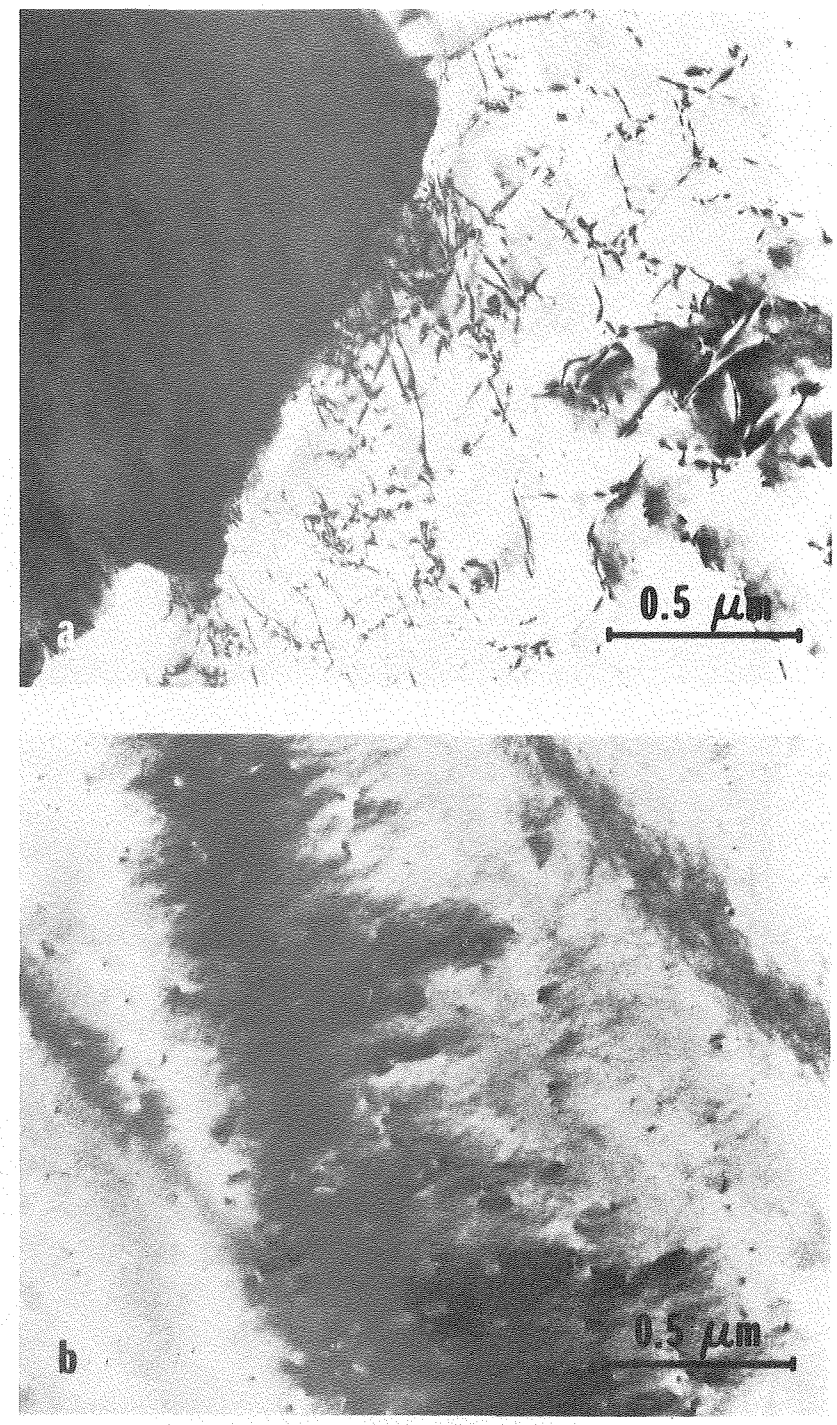

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Fig. 5

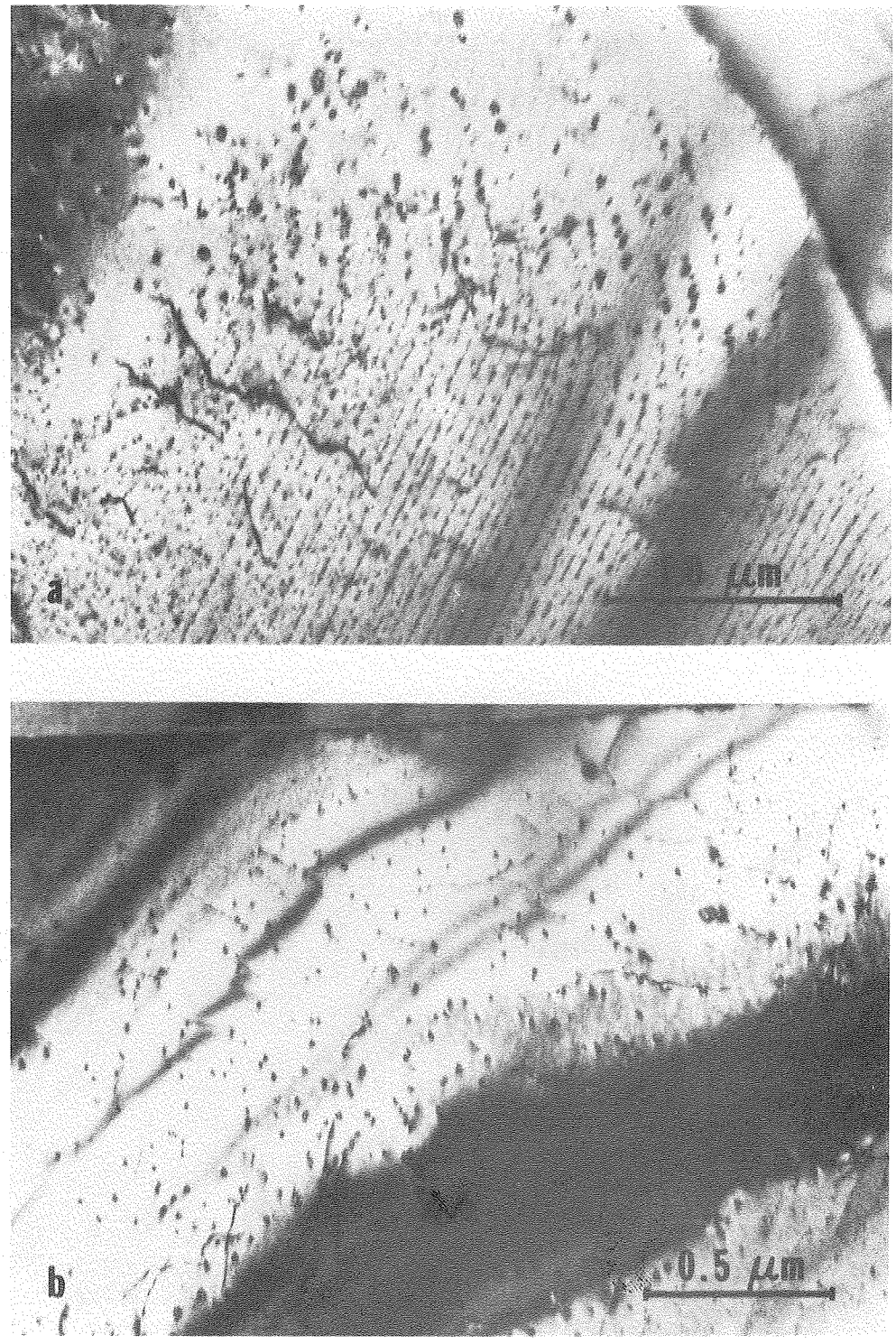

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Fig. 6