Title
ON THE PRECIPITATION OF EPSILON-CARBIDE IN LOWER BAINITE

Author
Lai, G.Y.

Publication Date
1974-07-01

Submitted to Metallurgical Transactions

LBL-2705
Preprint c.2

ON THE PRECIPITATION OF EPSILON-CARBIDE IN LOWER BAINITE

G. Y. Lai

July, 1974

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

DISCLAIMER

On the Precipitation of Epsilon-Carbide in Lower Bainite

G. Y. Lai

Inorganic Materials Research Division, Lawrence Berkeley Laboratory and Department of Materials Science and Engineering, College of Engineering; University of California, Berkeley, California 94720

ABSTRACT

The transformation mechanisms of bainite from metastable austenite has been a topic of debate for many years. The problem is complicated because the bainite transformation exhibits features common to both diffusion controlled and martensitic transformations.[1] It is known that there are two major forms of bainite; namely, upper and lower bainite. Recent transmission electron microscope studies[2,3] have shown that there is a distinct morphological difference between these two forms of bainite. In upper bainite, cementite precipitates between ferrite laths, while in lower bainite, cementite precipitates unindirectionally within the bainitic ferrite lath at an angle of about 55-65° to the long direction of the lath. The precipitation of ε carbide in lower bainite has also been observed,[4] although the precipitation process is not clearly understood. In a recent bainite debate,[5] Hehemann proposed the existance of the metastable eutectoid reaction $\gamma \rightleftharpoons \alpha + \varepsilon$ carbide at 350° C. He argued that below 350° C ε carbide precipitates very rapidly from supersaturated ferrite, since $\alpha - \varepsilon$ carbide is stable relative to $\alpha - \gamma$. This terminates the partition of carbon to austenite and results in a lower bainite

*Present address: General Atomics, P. O. Box 81608, San Diego, CA 92138

structure. In non-silicon steels, cementites will rapidly replace ε carbides analogous to tempering of martensite. Above 350° C the α - ε carbide aggregate is metastable relative to an α - γ aggregate. The upper bainites formed in non-silicon steels would contain cementites which could precipitate from both ferrite and austenite. In silicon steels, however, the precipitation of cementite is retarded due to the presence of silicon, the resulting upper bainites would be free of carbides. On the other hand, Kinsman and Aaronson[5] based on the measurements of bainite growth kinetics and of the carbon content of ferritic component of bainite, concluded that bainitic carbide is more likely to precipitate from austenite: ferrite boundaries. One possible approach to the answer of the question as to the source of bainitic carbide precipitation is to determine the crystallographic orientation relationship between carbide and ferrite in both upper and lower bainite. The crystallographic orientation relationship between cementite and ferrite in both bainites has been reported.[2,6-8] Shackleton and Kelly[2,6] found that some of the orientation relations observed between cementite and ferrite in upper bainite could only be related to the parent austenite. They then suggested that in upper bainite the cementite and ferrite can form separately in the parent austenite. As for lower bainite, the orientation relationship between cementite and ferrite has recently been reported to be the same as in tempered martensite.[2,6-8] However, there has been very limited evidence as to the crystallographic orientation relationship between ε carbide and ferrite in lower bainite. In this communication, direct evidence of the orientation relationship between ε carbide and ferrite in both lower bainite and tempered martensite is presented.

The steels investigated were AISI 4340 and 300M. They had the following composition (wt%),

	C	Mn	Cr	Ni	Mo	Si	Cu	S	P	V
4340	0.4	0.8	0.72	1.65	0.24	0.24	0.19	0.01	0.004	--
300M	0.41	0.79	0.75	1.85	0.43	1.59	0.04	0.002	0.008	0.08

Figure 1 shows the ε carbide in lower bainite for 300M steel isothermally transformed at 300°C for one hour after austenitizing at 870°C. The M_s temperature for this steel when austenitized at 870°C is 270°C.[9] The selected area diffraction (SAD) pattern obtained from Fig. 1a is shown in Fig. 1c. The diffraction pattern consists of $<111>_\alpha$ and $<100>_\alpha$ ferrite zones and $<11\bar{2}0>_\varepsilon$ carbide zone, Fig. 1c,d. It was determined by the dark field imaging technique that lath A exhibits $<111>_\alpha$ orientation whereas lath B $<100>_\alpha$ orientation. The ferrite laths with alternative $<111>_\alpha$ and $<100>_\alpha$ orientations were frequently observed in dislocated lath martensite.[10] A dark field image, Fig. 1b, was formed by the diffraction spot A in Fig. 1c, showing the reversal contrast of ε carbides and lath A. The diffraction Spot A, which is shown in Fig. 1c and is indexed in Fig. 1d, is a superposition of two diffraction spots, one from $<111>_\alpha$ zone and the other from $<11\bar{2}0>_\varepsilon$ carbide zone. Since lath B exhibits $<100>_\alpha$ orientation and ε carbide in lath B exhibits $<11\bar{2}0>_\varepsilon$ carbide orientation, the orientation relationship of $<100>_\alpha \| <11\bar{2}0>_\varepsilon$ carbide in lower bainite was unambiguously determined. A lath between lath A and lath B was also observed in Fig. 1b. It has the same orientation as that of lath B based on selected area diffraction and dark field analyses. However, no carbides were observed within the lath. It is not clear whether it is a bainitic ferrite lath or a martensitic ferrite lath. Nevertheless, the sample was isothermally transformed for one hour followed by oil quench, the transformation of austenite to bainite could not possibly be complete. Thus, the lath is likely to be a martensite lath which was formed during quenching after isothermal transformation.

Figure 2 shows the ε carbide in autotempered lath martensite for AISI 4340 steel austenitized at 1200°C and quenched into room temperature oil. The ε carbides were formed during quenching. Except for the diffraction spot B which was identified as an austenite reflection from retained austenite films formed between martensite laths, the SAD pattern, Fig. 2c, obtained from Fig. 2a is the same as that in Fig. 1c. Verification of this unusual microstructure of retained austenite films between martensite laths was made by examining several foils. A (110) austenite diffraction pattern was observed in some cases. A detailed analysis showing the presence of significant amount of retained austenite films between martensite laths in the as-quenched AISI 4340 which was austenitized at 1200°C was presented recently by Lai, et al.[11] They further observed that this austenite was stable even at liquid nitrogen temperature (-196°C). The diffraction pattern of Fig. 2c consists of $\langle 111 \rangle_\alpha$ and $\langle 100 \rangle_\alpha$ ferrite zones representing the orientations of laths A and B respectively, and a weak $\langle 11\bar{2}0 \rangle_\varepsilon$ carbide zone. The ε carbide diffraction spots in Fig. 2c are weak and are not as readily recognizable as in Fig. 1c. However, a dark field image, Fig. 2b, formed by the diffraction spot A, superimposed by two diffraction spots, one from $\langle 111 \rangle_\alpha$ zone and the other from $\langle 11\bar{2}0 \rangle_\varepsilon$ carbide zone, shows the reversal contrast of the lath A and ε carbides. The lath B exhibits $\langle 100 \rangle_\alpha$ orientation, and the ε carbide in the lath B exhibits $\langle 11\bar{2}0 \rangle_\varepsilon$ carbide orientation. Thus, the orientation relationship of

$\langle 100 \rangle_\alpha \parallel \langle 11\bar{2}0 \rangle_\varepsilon$ carbide was observed to exist in tempered martensite.

The orientation relationship of $\langle 100 \rangle_\alpha \parallel \langle 11\bar{2}0 \rangle_\varepsilon$ carbide in tempered martensite was also observed by Murphy, et al.[12] They indicated this orientation relationship was consistent with the Jack relationship[13] in tempered martensite, i.e., $(0001)_\varepsilon$ carbide $\parallel$ $(011)_\alpha$ and $(10\bar{1}1)_\varepsilon \parallel (101)_\alpha$, within 1 to 2°.[12] In an Fe-0.5% C-1.87% Si steel, Huang and Thomas[14] recently observed ε carbide in lower bainite, and the orientation relationship was found to follow the Jack relationship.

It is clearly shown in the present investigation that the orientation relation of $\langle 100 \rangle_\alpha \parallel \langle 11\bar{2}0 \rangle_\varepsilon$ carbide was observed in both lower bainite and tempered lath martensite. This would support the view that in lower bainite, carbides precipitate directly from supersaturated ferrite.

It is also interesting that the ε carbide, observed in Figs. 1 and 2, forms on $\{100\}_\alpha$ planes and grows in $\langle 100 \rangle_\alpha$ directions in both lower bainite and tempered martensite. However, in tempered martensite two variants of ε carbide were observed, while in lower bainite only one variant that is a typical lower bainite structure was observed. Further study of the reasons for this difference between lower bainite and tempered martensite might produce new information about the transformation mechanism of lower bainite.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to Professor E. R. Parker and Professor V. F. Zackay for their continued guidance and 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.

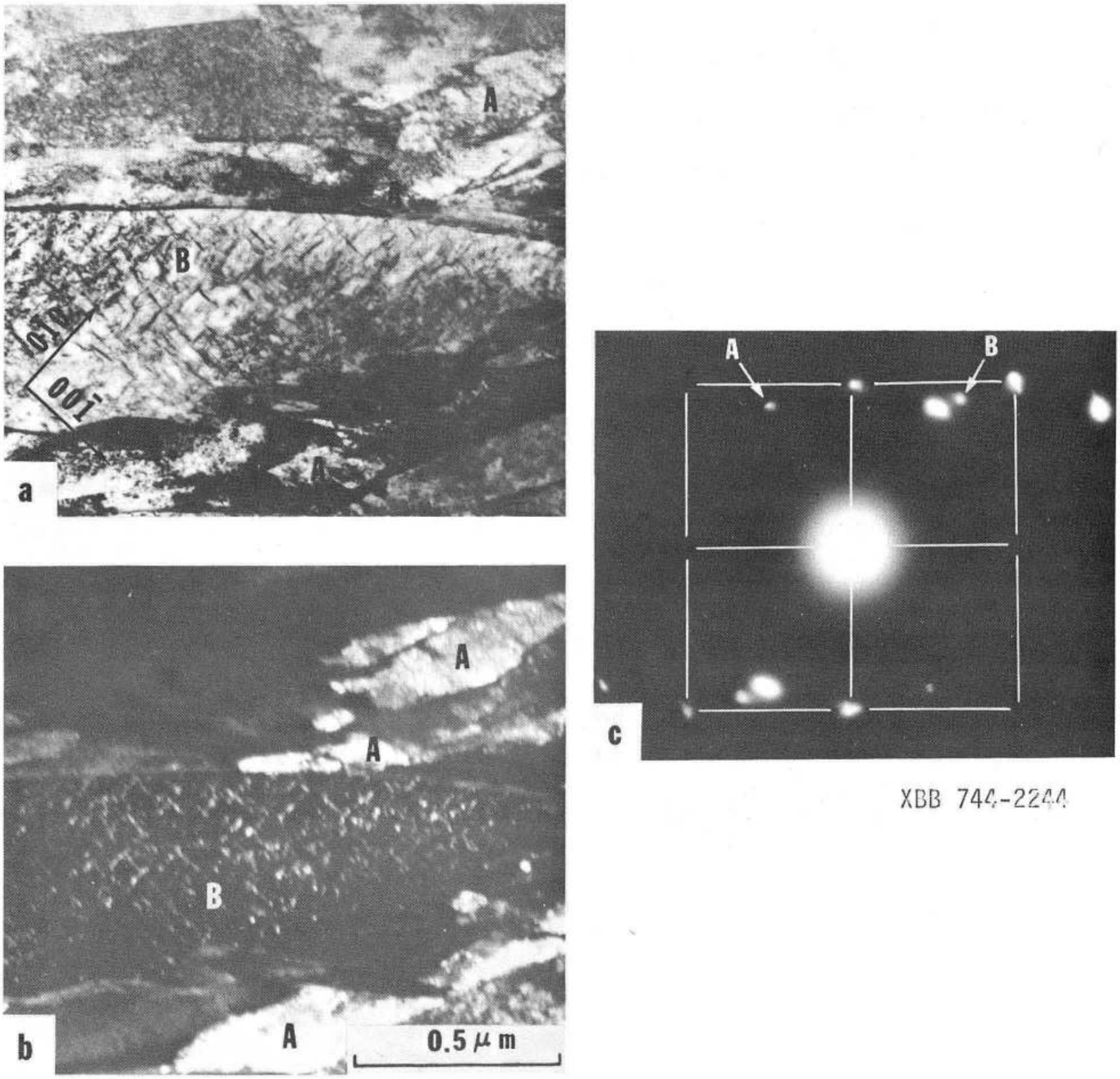
REFERENCES

1. R. F. Hehemann: Phase Transformation, p. 397, American Society for Metals, Metals Park, Ohio, 1970.
2. D. N. Shackelton and P. M. Kelly: Special Report 93, p. 126, The Iron and Steel Institute, London, 1965.
3. G. Thomas: Iron and Steel International, October 1973, p. 451.
4. J. M. Oblak and R. F. Hehemann: Transformation and Hardenability in Steels, p. 15, Climax Molybdenum Company of Michigan, Ann Arbor, Michigan, 1967.
5. R. F. Hehemann, K. R. Kinsman, and H. I. Aaronson: Met. Trans., 1972, Vol. 3, p. 1077.
6. D. N. Shackelton and P. M. Kelly: Acta Met., 1967, Vol. 15, p. 979.
7. E. R. Kuteliya and L. M. Utevskiy: Fiz. Metal. Metalloved, 1969, Vol. 28(1), p. 129.
8. F. B. Pickering: Transformation and Hardenability in Steels, p. 109, Climax Molybdenum Company of Michigan, Ann Arbor, Michigan, 1967.
9. C. E. Erickson: M.S. Thesis, University of California, Berkeley, California, LBL-2279, 1973.
10. S. K. Das and G. Thomas: Trans. ASM, 1969, Vol. 62, p. 659.
11. G. Y. Lai, W. E. Wood, R. A. Clark, V. F. Zackay, and E. R. Parker: Met. Trans., 1974, Vol. 5, p. 1524.
12. S. Murphy and A. Whiteman: Met. Trans. 1970, Vol. 1, p. 843.
13. K. H. Jack: J. Iron Steel Inst., 1951, Vol. 169, p. 26.
14. D. H. Huang and G. Thomas: Unpublished research, University of California, Berkeley, CA, 1973.

FIGURE CAPTIONS

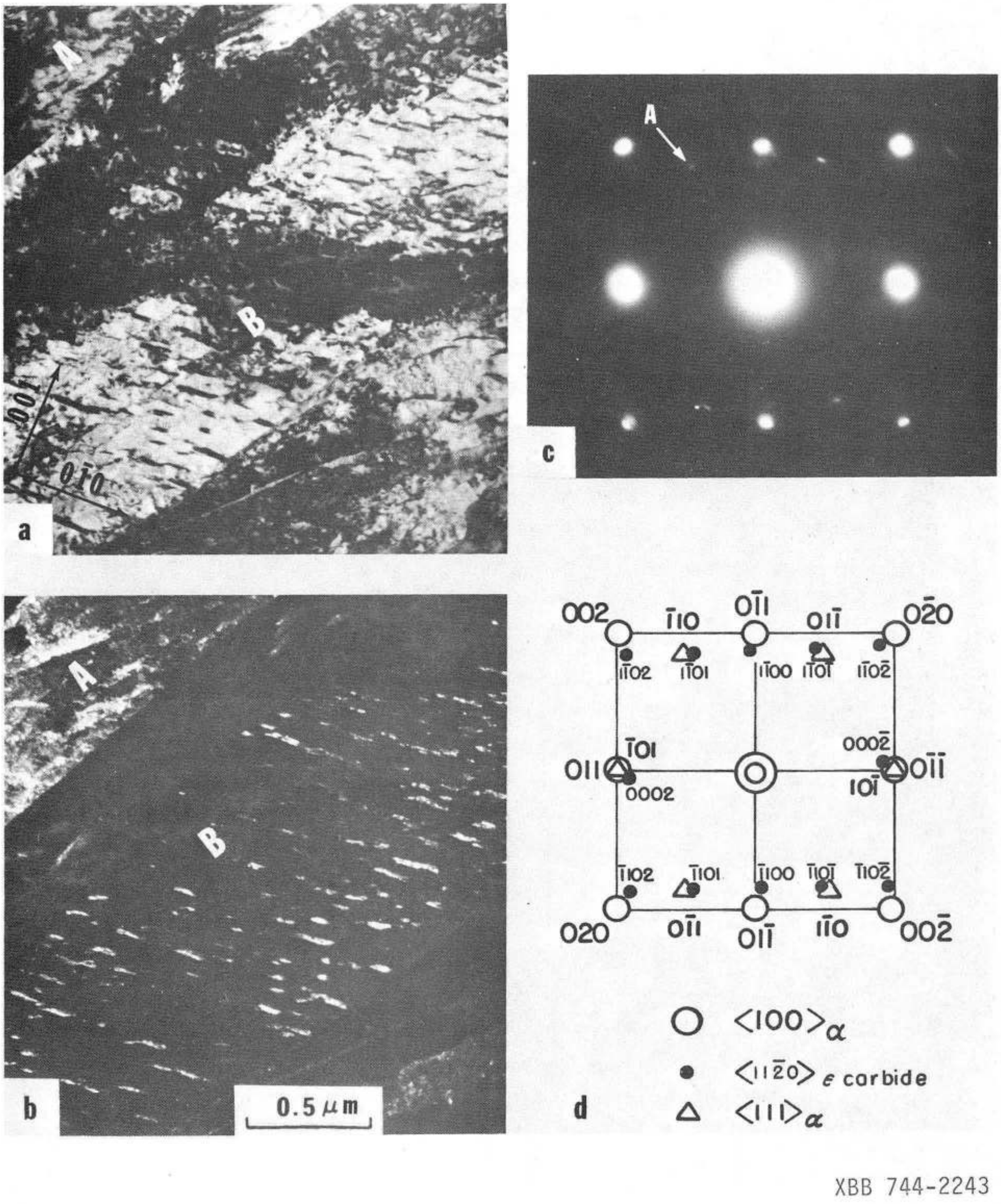
Fig. 1. ε carbides in lower bainite for 300M steel isothermally transformed at 300°C for 1 hr. (a) Bright field image, (b) dark field image of the reflection A which was superimposed by $(\bar{1}10)_\alpha$ ferrite spot (from $\langle 111\rangle_\alpha$ zone) and $(1\bar{1}01)_\varepsilon$ carbide spot, showing the reversal contrast of the lath A ($\langle 111\rangle_\alpha$ zone) and ε carbides in the lath B ($\langle 100\rangle_\alpha$ zone), (c) SAD pattern, and (d) Schematic sketch of the SAD pattern with the three different sets of diffraction pattern indexed.

Fig. 2. ε carbides in autotempered martensite for AISI 4340 steel quenched in oil after austenitizing at 1200°C. (a) Bright field image, (b) dark field image of reflection A which was superimposed by a ferrite diffraction spot (from $\langle 111\rangle_\alpha$ zone) and an ε carbide diffraction spot, showing the reversal contrast of the lath A ($\langle 111\rangle_\alpha$ zone) and ε carbides in the lath B ($\langle 100\rangle_\alpha$ zone), and (c) SAD pattern.



XBB 744-2244

Fig. 2



XBB 744-2243

Fig. 1

TECHNICAL INFORMATION DIVISION
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720