Materials Transactions, JIM, Vol. 32, No. 8 (1991), pp. 705 to 714

Bainite Structures in 0.2C–3.6Ni Steel

A. Joarder* and D. S. Sarma*

The microstructures of a 0.2C–3.6Ni steel are studied after isothermal transformation over a temperature range of 600–400°C after different times up to 10 ks at each temperature. It was observed that the transformation at 600°C and 500°C for short durations has led to the formation of Widmanstätten ferrite-martensite structures (the later formed as a result of transformation during cooling of untransformed austenite) which on further holding led to the formation of cementite allotriomorphs at ferrite grain boundaries (at 600°C) or bainite (at 500°C) structures. This reveals that the ferrite-martensite structures, referred to as BI type of bainite proposed by earlier investigators is not bainitic in nature. Transformation at 450°C resulted in mixed structures of upper bainite and lath-type lower bainite while lath type lower bainite only formed at 400°C. It was found that nickel has strong stabilising effect on retaining austenite films at the lath boundaries of martensite as compared with manganese or molybdenum.

(Received February 16, 1991)

Keywords: *bainite, microstructure, isothermal transformation, austenite*

I. Introduction

Ever since Davenport and Bain[1] reported the formation of bainite in their pioneering work on isothermal transformation of a eutectoid steel, there have not only been several research investigations confirming the formation of bainite, a non-lamellar aggregate of ferrite and cementite formed during austenite transformation at temperatures just below that of pearlite reaction, but several authoritative review papers[2]-[7] have also since been published. Although the bainitic transformation is considered to follow its own kinetics with a B_s temperature (below which only the bainitic reaction takes place) and is also seen from the viewpoint of shear (based on the observation of surface upheavals), there has been considerable controversy in the understanding of bainitic transformation mechanisms based on these criteria[8]. Accordingly, the microstructural definition of bainite seems to be universally accepted. While two distinct morphologies of bainite viz., upper bainite (with carbides along the lath boundaries of ferrite) and lower bainite (with carbide precipitation within ferrite at a sharp angle to the plate boundary) are formed in a wide variety of plain carbon and low alloy steels, other morphological forms like nodular bainite[9]-[12] and inverse bainite[13][14] are reported in high carbon steels. In the case of low carbon low alloy steels, Ohmori *et al.*[15] reported BI, BII and BIII type bainites comprising respectively of carbide-free bainite, typical upper bainite and lath-type lower bainite. There have been other investigations to report carbide-free bainite. For instance, Kang *et al.*[16] termed such bainite in low alloy steels as meta-bainite. Bramfitt and Speer[17] have recently given yet another classification of bainite morphologies, B_1, B_2 and B_3 which respectively contain intralath carbides, interlath carbides and discrete regions of retained austenite or martensite in acicular ferrite. There has also been some controversy as to whether upper and lower bainites form in two distinctly separate temperature regions or whether both can form at the same temperature[18][19].

The present investigation has been taken up to specifically understand the nature of carbide-free bainite in low carbon low alloy steels and also to know the temperature range of formation of upper and lower bainites in such steels. The results obtained on a 0.2C–3.6Ni steel are presented in this paper while those on Mn and Mo steels will be discussed elsewhere[20].

II. Experimental Procedure

The chemical composition of the steel used in the present investigation is given in Table 1. The steel ingot of about 10 kg was hot forged to 20 mm thick plate and 3 mm thick sheets cut from this forged plate were cold rolled to 1 mm thickness. Samples from this sheet were austenitised at 1050°C for 30 min in a salt bath containing 90% barium chloride and 10% sodium chloride. The samples were rapidly transferred after a sustenitising to another salt bath furnace containing sodium nitrate and potassium nitrate for isothermal reaction and were water quenched immediately after the required time of isothermal reaction. Thin foils for transmission electron microscopy were prepared by window technique using an electrolyte containing 90% glacial acetic acid and 10% perchloric acid. Thin foils were examined in a JEOL 200 CX transmission electron microscope using an operating voltage of 160 or 200 kV.

Table 1 Chemical composition (mass%) of the steel investigated.

C	Mn	Si	S	P	Ni
0.20	0.48	0.325	0.024	0.020	3.65

* Department of Metallurgical Engineering, Institute of Technology, Banaras Hindu University, VARANASI-221 005, India

III. Results

1. Transformation at 600°C

Figure 1 is a transmission electron micrograph (TEM) showing Widmanstätten ferrite and martensite (dark area) in the steel after isothermal holding for 100 s at 600°C. The martensite area at higher magnification and its dark field from (011) twinning reflection are shown in Fig. 2(a) and (b) respectively. The selected area diffraction pattern (SAD) showing both matrix and twin reflections and its schematic representation are displayed in Fig. 2(c) and (d) respectively. It has been observed in some other areas of the foil that the transformation product is polygonal ferrite and cementite along the grain boundaries, Fig. 3(a). The SAD shown in Fig. 3(b) and its schematic representation in Fig. 3(c) identify the grain boundary carbide to be cementite. Increasing the isothermal transformation time to 10 ks has not initiated the pearlite transformation and the TEMs obtained were similar to that of Fig. 3(a).

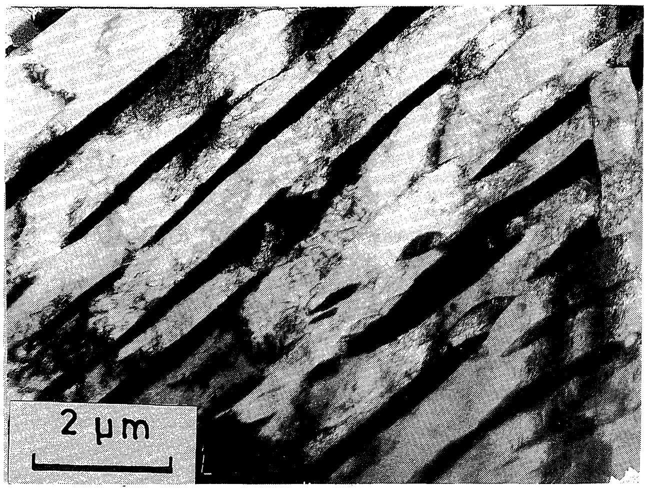


Fig. 1 TEM of the steel isothermally transformed at 600°C for 100 s showing Widmanstätten ferrite (white area) and martensite (dark area).

2. Transformation at 500°C

Figure 4(a) reveals ferrite and martensite (formed from untransformed austenite) for 100 s isothermal holding at 500°C while Fig. 4(b) is a TEM from another area of the foil revealing pearlite. This pearlite morphology is not strictly lamellar and may arise as a transition between

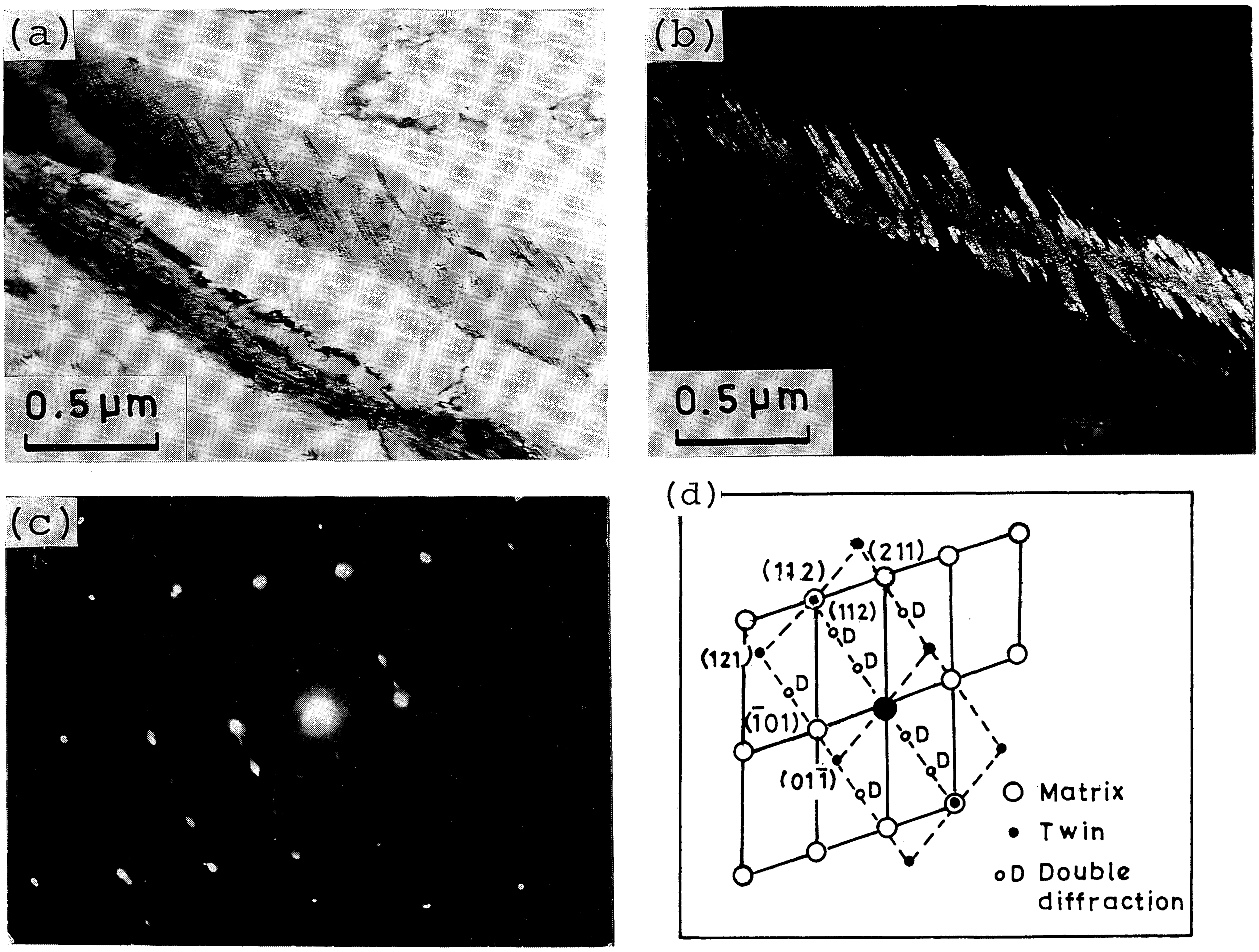


Fig. 2 Same treatment as in Fig. 1. (a) BF (b) DF taken from twinning reflection, (c) SAD, (d) its schematic represention.

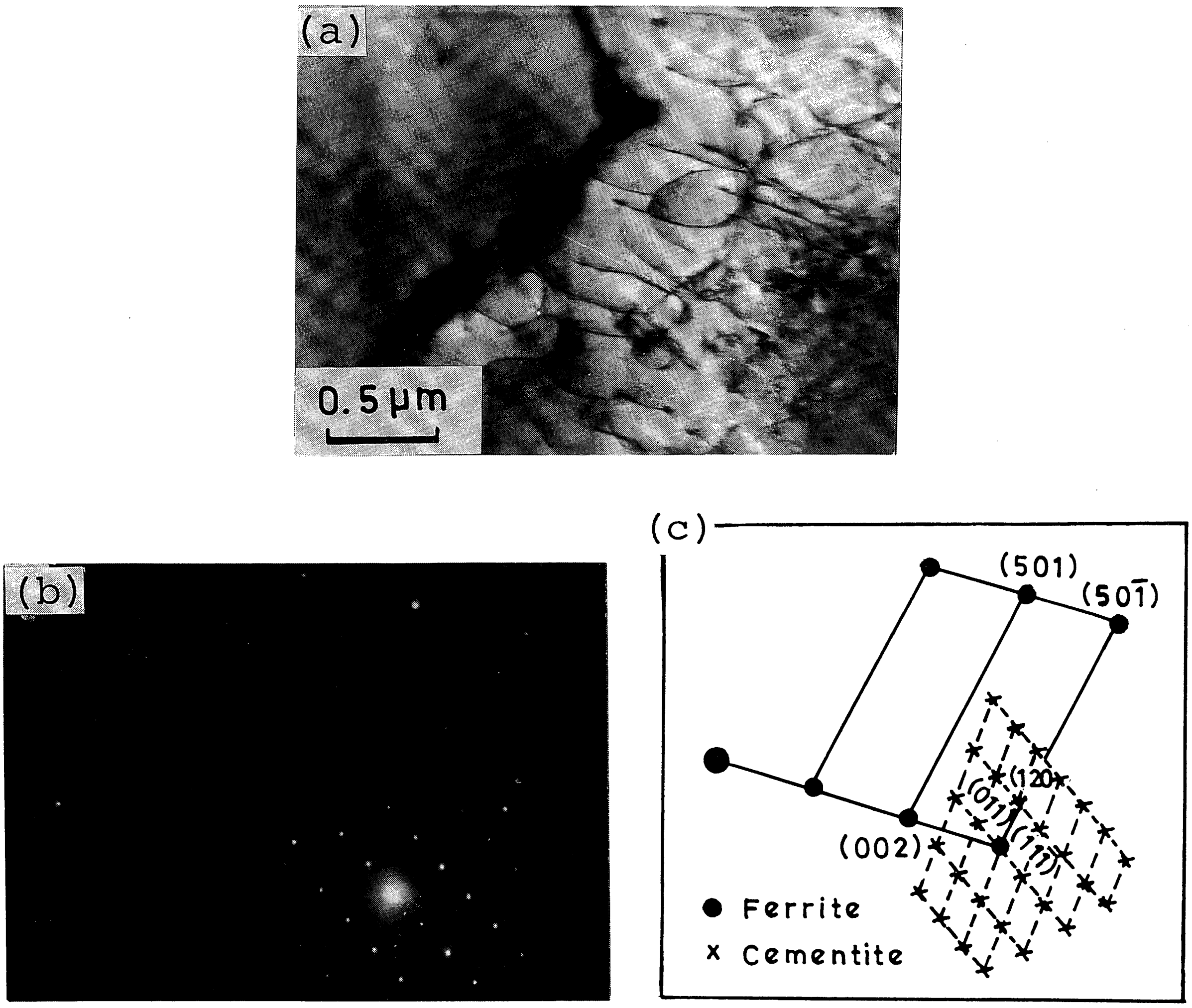


Fig. 3 TEMs for 600°C, 100 s (a) shows cementite along the grain boundaries (b) SAD from grain boundary cementite, (c) its schematic representation.

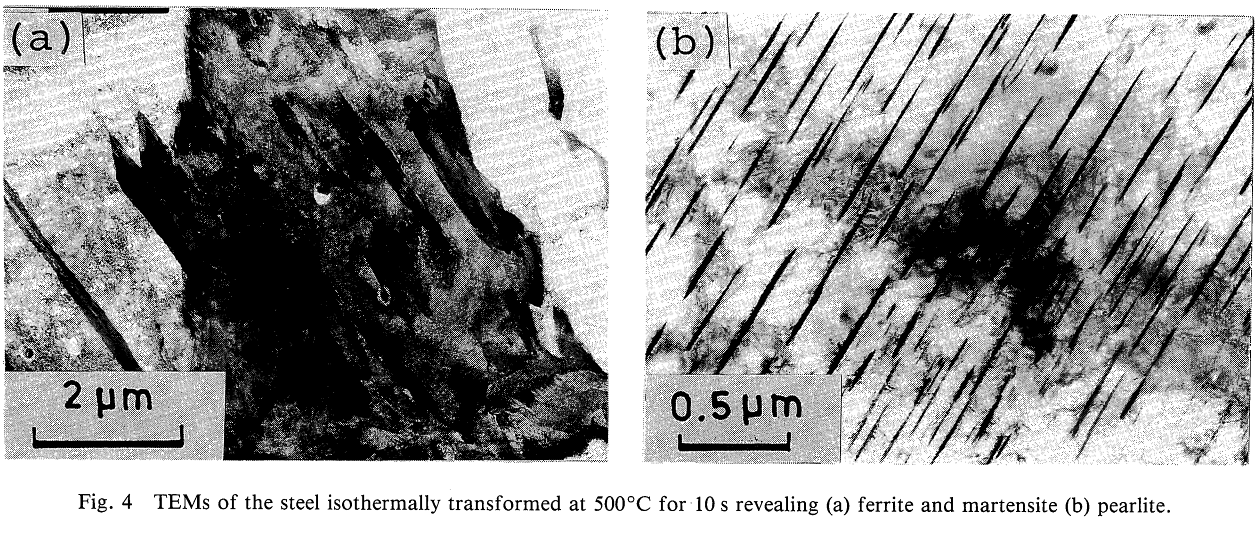


Fig. 4 TEMs of the steel isothermally transformed at 500°C for 10 s revealing (a) ferrite and martensite (b) pearlite.

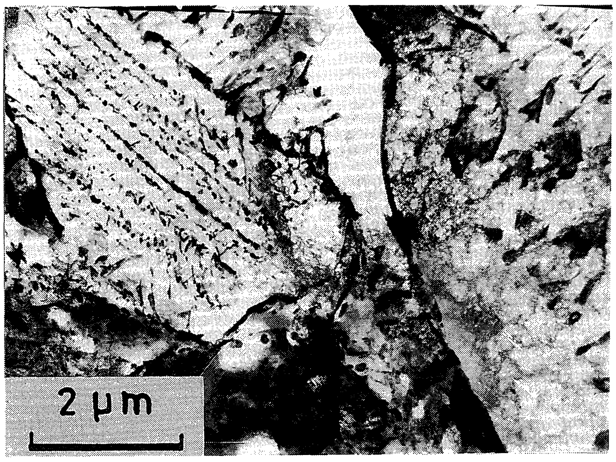


Fig. 5 TEM of steel transformed at 500°C for 10 ks revealing discrete cementite precipitates.

pearlite and upper bainite. This plate type precipitate has been identified by SAD to be cementite. Figure 5 is a TEM for 1 ks isothermal holding and reveals discrete cementite precipitation in ferrite. A low magnification TEM for 10 ks isothermal holding is shown in Fig. 6(a) revealing typical upper bainite morphology. Figure 6(b) and (c) are bright field micrograph (BF) and dark field micrograph (DF) revealing carbide precipitates along the lath boundaries. The SAD from this area and its schematic representation shown in Fig. 7(a) and (b) respectively, permits to identify these lath boundary carbides as cementite.

3. Transformation at 450°C

The TEMs of the steel after isothermal transformation at 450°C for 2 s have revealed the presence of martensite laths with retained austenite along the lath boundaries as shown in BF and DF of Fig. 8(a) and (b) respectively. Figure 8(c) is the corresponding SAD and Fig. 8(d) its schematic representation, identifying the lath boundary films as austenite. The following orientation relationship (OR) is observed between austenite (γ) and ferrite (α):

$$(111)_\gamma \quad // \quad (101)_\alpha$$
$$(010)_\gamma \quad 5^\circ \text{ with } \quad (011)_\alpha$$
$$(111)_\gamma \quad 5^\circ \text{ with } \quad (110)_\alpha$$

This OR follows that of Kurdjumov-Sachs[21].

The TEMs of the steel transformed at 450°C for 10 s are shown in Fig. 9. Figure 9(a) and (b) clearly reveal both lath and plate morphologies of bainite. Cementite is observed both along the lath boundaries and on planes sharply inclined to the lath or plate boundaries, Fig. 9(b). The dark massive areas shown in these figures are martensite formed from untransformed austenite. Figure 10

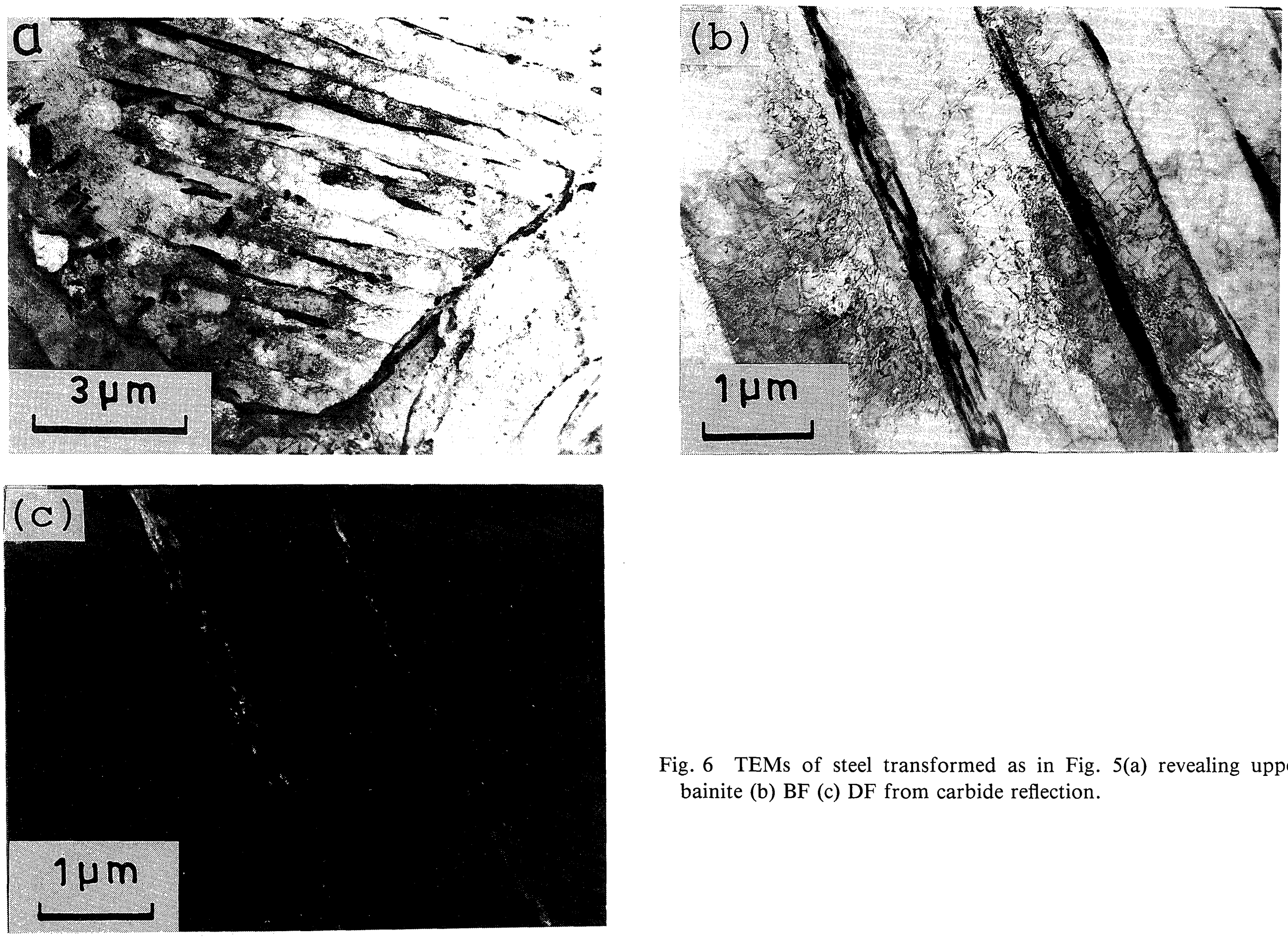


Fig. 6 TEMs of steel transformed as in Fig. 5(a) revealing upper bainite (b) BF (c) DF from carbide reflection.

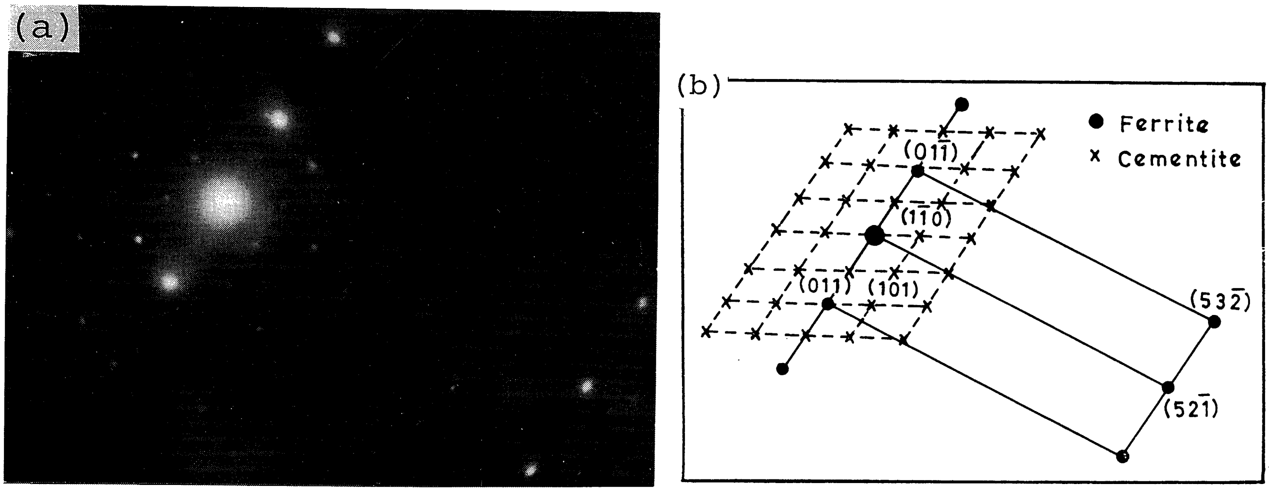


Fig. 7 (a) SAD and (b) its schematic representation for the area shown in Fig. 6(b) and (c).

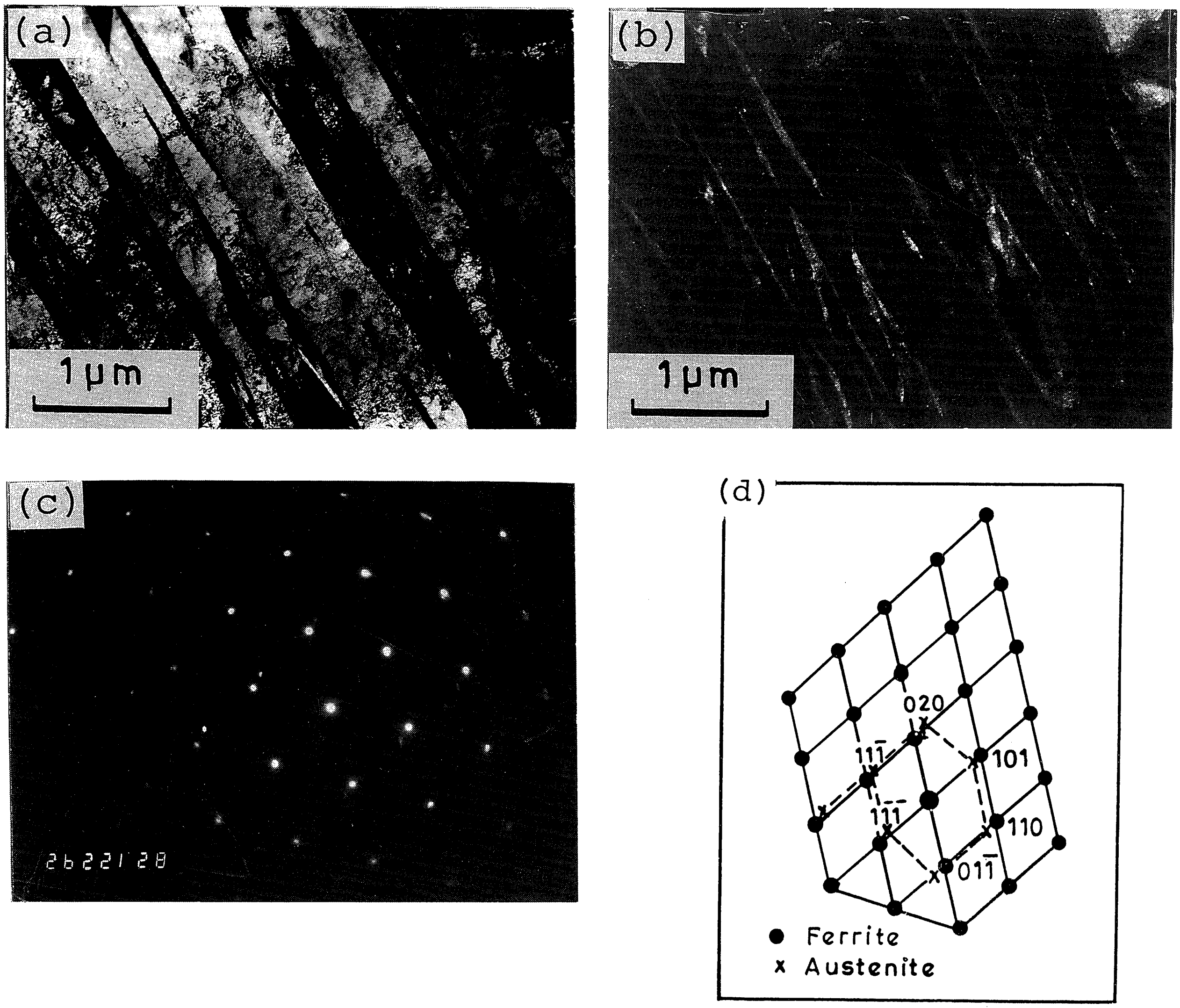


Fig. 8 TEMs of the steel isothermally transformed at 450°C for 2 s (a) BF, (b) DF, (c) SAD, (d) its schematic representation.

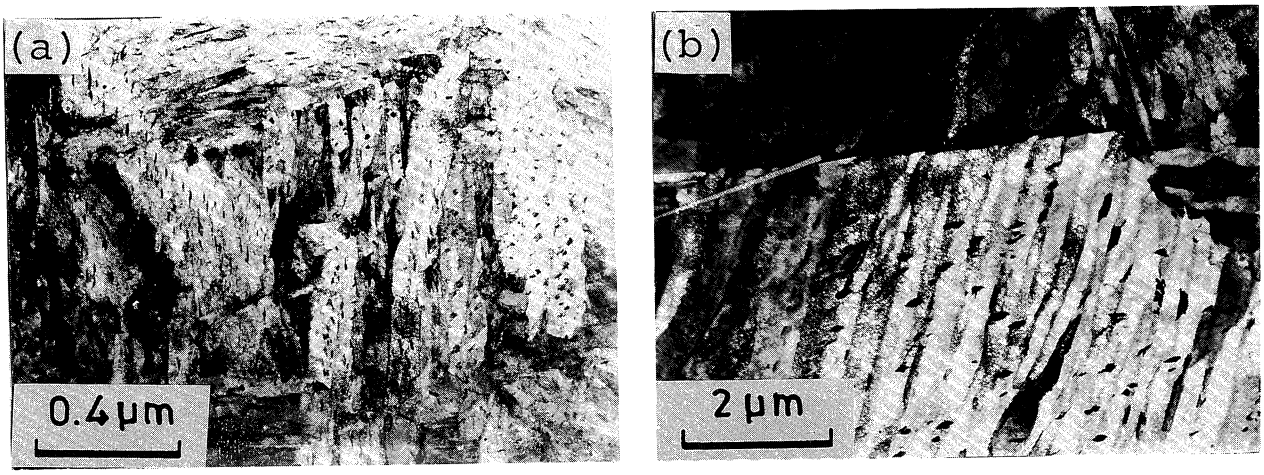


Fig. 9 TEMs of the steel isothermally transformed at 450°C for 10 s (a) and (b) revealing lath and plate morphologies of bainite.

(a) is a TEM of the steel isothermally transformed at 450 °C for 100 s revealing carbide precipitates along the lath boundaries. The corresponding SAD shown in Fig. 10(b) and its schematic representation in Fig. 10(c) identifies this carbide to be cementite. Cementite has the following orientation relationship (OR) with ferrite:

$$(100)_c \parallel (011)_\alpha$$
$$(121)_c \parallel (101)_\alpha$$
$$(021)_c \parallel (211)_\alpha$$

The OR follows that of Bagaryaskii[18].

The transformation products observed after 1 ks isothermal holding are similar to those of 100 s. Figure 11(a) is a TEM revealing coarse cementite precipitates along the lath boundaries of ferrite in upper bainite. Figure 11(b) is a TEM revealing the structure after 10 ks at 450°C giving typical upper bainitic type structure.

4. Transformation at 400°C

The transformation of austenite has started when the

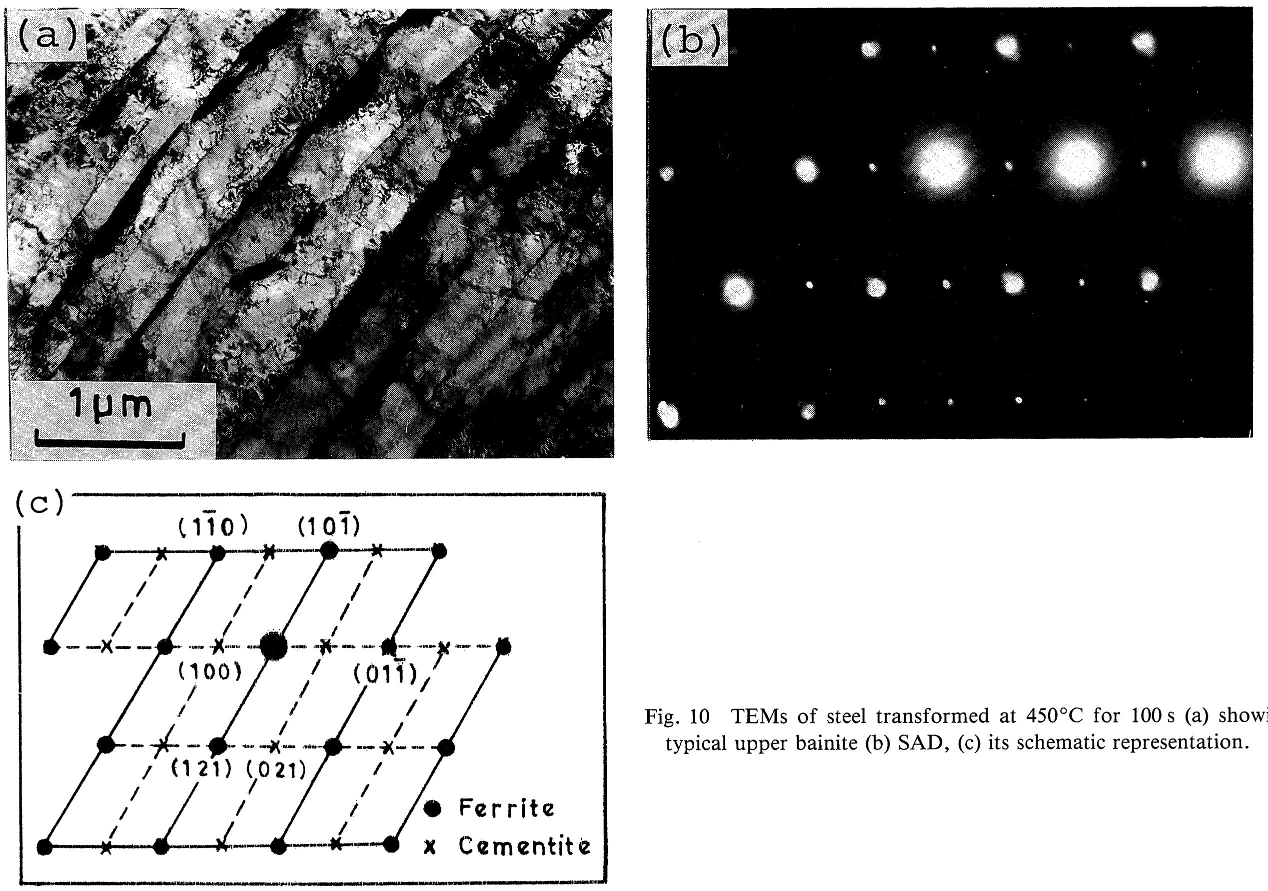
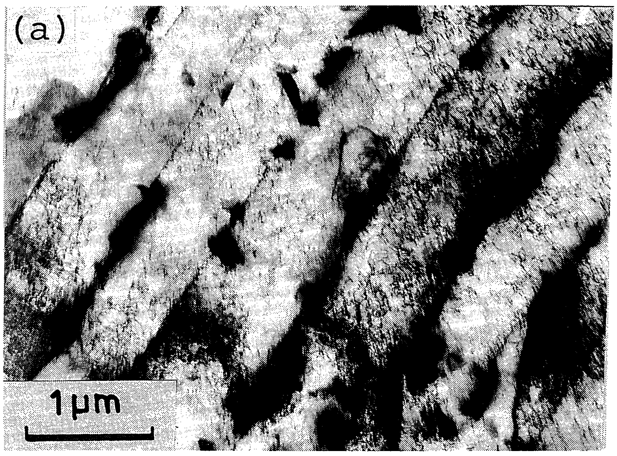


Fig. 10 TEMs of steel transformed at 450°C for 100 s (a) showing typical upper bainite (b) SAD, (c) its schematic representation.



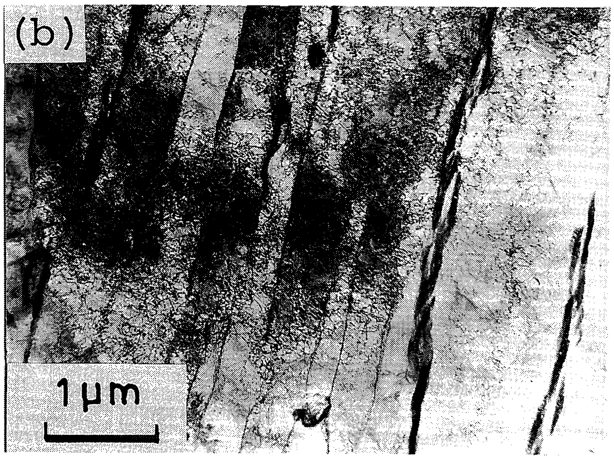


Fig. 11 TEMs of the steel isothermally transformed at 450°C for 1 ks (a) and (b) revealing upper bainite.

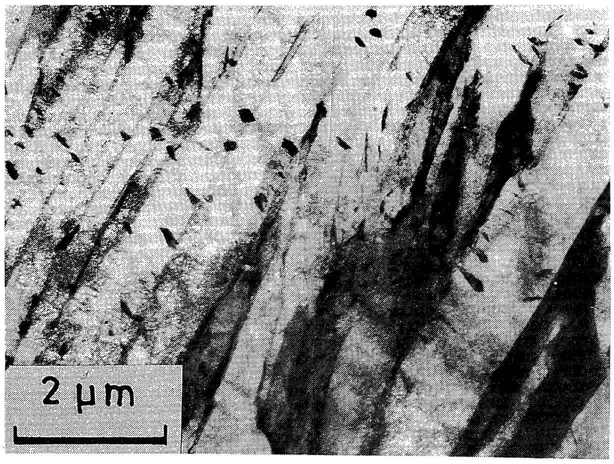


Fig. 12 TEM of the steel isothermally transformed at 400°C for 10 s revealing lath type bainite and martensite (dark area).

isothermal holding time is about 10 s. Figure 12 clearly reveals bainite structure and martensite (dark area) formed from untransformed austenite. Other areas of the foil exhibited martensite laths with retained austenite along the lath boundaries as demonstrated in Fig. 13(a) and (b), BF and DF respectively. The corresponding SAD and its schematic representation in Fig. 13(c) and (d) permits to identify these lath boundary films as austenite. Ferrite follows an OR with austenite as given below:

$$(011)_\alpha \quad // \quad (111)_\gamma$$
$$(101)_\alpha \quad 5^\circ \text{ with } \quad (100)_\gamma$$
$$(110)_\alpha \quad 7^\circ \text{ with } \quad (111)_\gamma$$

This OR follows that of Kurdjumov-Sachs[21].

Figure 14(a) is a TEM of steel isothermally transformed at 400°C for 1 ks showing bainite laths and cementite precipitation within the laths. Some other areas of the foil display plate type lower bainite with cementite at a sharp angle to the interface as shown in Fig. 14(b) and (c), BF and DF respectively.

IV. Discussion

The results of the present investigation on the isothermal transformation products of austenite in the 0.2%C–3.6%Ni steel over the temperature range of 400–600°C are summarised in Table 2.

The initial decomposition product of austenite at 600°C is Widmanstätten ferrite, Figs. 1, 2 and 4(a) (as the martensite present in these TEMs has formed due to the transformation during quenching of the untransformed austenite). Further transformation of austenite at 600°C has resulted in the formation of polygonal ferrite with cementite precipitating at the grain boundaries of ferrite (pearlite has not formed even after 10 ks at this temperature). These cementite allotriomorphs have reached a size of 0.1 μm in diameter and have formed as continuous films in several areas, Fig. 3(a). This observation that the presence of nickel would promote the precipitation of cementite at the ferrite grain boundaries at the expense of the pearlite transformation is in accordance with the finding of Chilton and Speich[22] who reported similar structures in a 5% Ni steel. This effect of nickel is thus different from that of manganese which when present in the steel in substantial amounts would cause pearlite formation at 600°C[20]. The ferrite formed at 500°C in the initial stages of austenite decomposition has the characteristics of massive ferrite as well as those of Widmanstätten ferrite in different regions of the foil examined. In the case of steels with strong carbide forming elements like Cr and Mo, Boswell *et al.*[23] as well as Tsubakino and Aaronson[24] reported that the ferrite was of Widmanstätten morphology at both high temperatures above the bay and at temperatures below the bay but was slightly degenerate when formed at temperatures close to the bay region.When the amounts of these elements was insufficient to cause the bay in the TTT curves, there was a notch in them and in this case the ferrite morphology was Widmanstätten when formed at the notch temperature as well. This degeneracy in ferrite

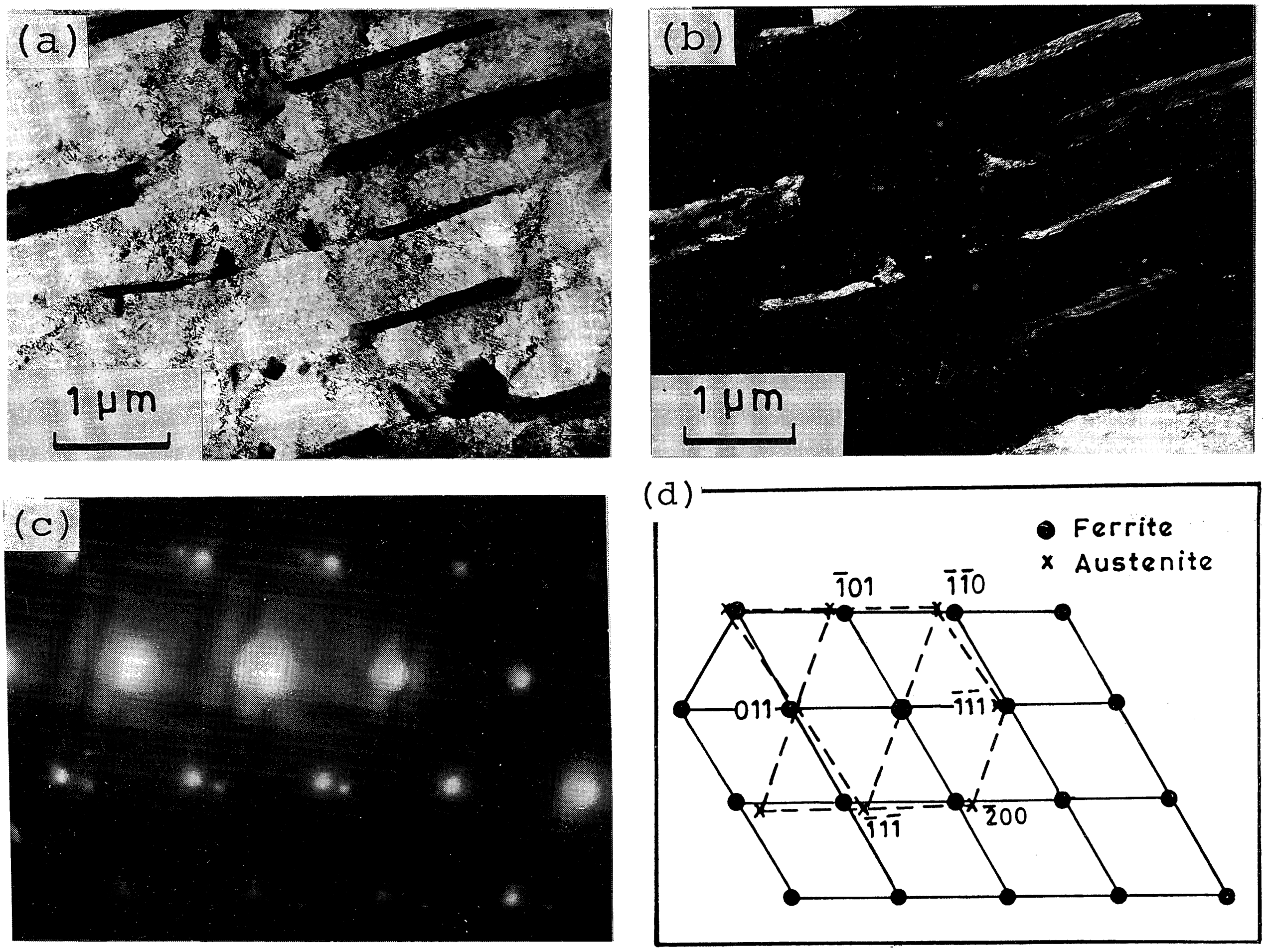


Fig. 13 Same treatment as in Fig. 12 (a) BF (b) DF (c) SAD (d) its schematic representation.

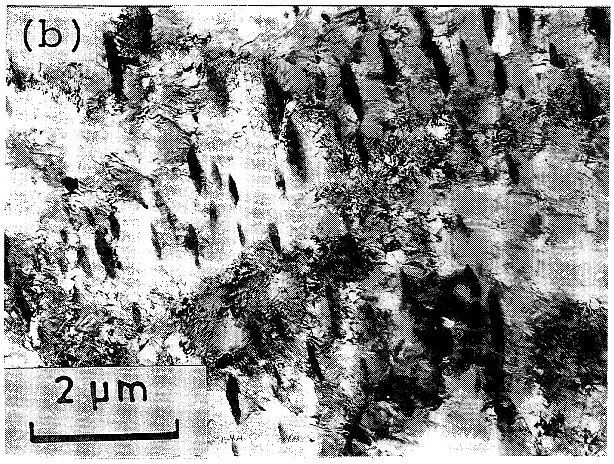
observed by these earlier investigators may correspond to the massive features of ferrite observed at 500°C in our work.

On the basis of isothermal transformation studies on low carbon low alloy steels, Ohmori *et al.*[15] concluded that three morphological forms of bainite could occur. These three, designated as BI, BII and BIII respectively are carbide-free bainite occurring in the temperature range 600–500°C, conventional upper bainite at 525–450°C and lath-type lower bainite at 450–400°C. The results of the present investigation reveal that all these morphological forms exist in the nickel steel investigated and that while the BII and BIII morphologies of upper bainite and lath-type lower bainites are the end products of transformation at 500 and 400°C respectively, the BI bainite is not. This Widmanstätten ferrite-martensite formation in alternate layers is found in the present work to be only a transitory structure which ultimately gives way to pearlite or bainite formation. The non-observation of this final structure by Ohmori *et al.*[15] could be due to the cumulative hardenability effect of the various alloying elements (Cu–Ni–Cr–Mo) in their steel which would shift the TTT curve to much longer times, beyond those studied by Ohmori *et al.*[15]

The Widmanstätten ferrite-martensite/retained austenite structures have also been reported by other investigators, both on isothermal transformation as well as after continuous cooling from austenitic condition. Mou and Hsu[25] observed that BI type bainite formed in a low carbon low alloy steel when isothermally transformed at 600°C. Liu and Zhang[26] also observed intralath austenite films in a 0.14C–2Mn–0.1Ti steel when transformed at 500°C and Kang *et al.*[16] observed such "meta-bainite" structures in a medium carbon low alloy steel. Lee *et al.*[27][28] observed martensite/retained austenite coexisting with acicular ferrite in a low carbon low alloy steel continuously cooled from the austenitic state.

The fact that the Widmanstätten ferrite/martensite structure has transformed on further isothermal transformation at the same temperature to upper bainite does not entitle itself to be designated as bainite. This conclusion is also in agreement with the observation of Reynolds *et al.*[29] who after a study of several Fe–C–X alloys concluded that only the ferrite-carbide non-lamellar structures be considered as bainite and the ferrite-austenite ones as due to proeutectoid ferrite formation.

The present investigation also confirms that both upper bainite and lower bainite form on isothermal transformation of the nickel steel at 450°C. While this result is



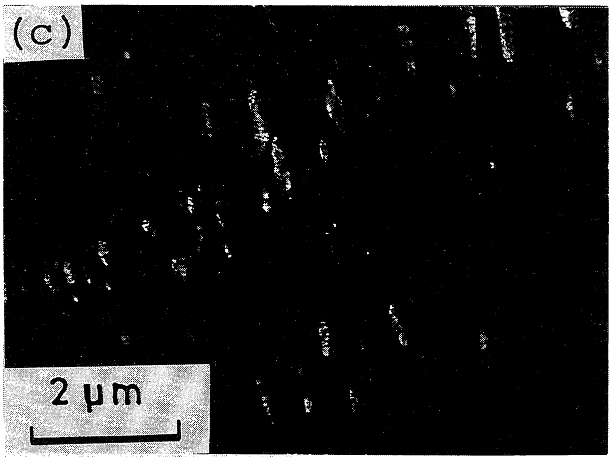


Fig. 14 TEMs of the steel isothermally transformed at 400°C for 1 ks (a) revealing BIII type bainite, (b) BF, (c) DF revealing lower bainite.

Table 2 Summary of isothermal transformation products.

Temperature (°C)	Transformation products
600	WF+M ⟶ WF+PF+Fe_3C
	100 s 10 ks
500	WF+M+B/P ⟶ WF+UB
	10 s 10 ks
450	M+RA ⟶ LB+UB+M ⟶ LB+UB
	2 s 10 s 1 ks
400	M+RA+LB ⟶ LB
	10 s 1 ks

B: Bainite, M: Martensite, P: Pearlite, PF: Polygonal,
WF: Widmanstätten, LB: Lower Bainite,
UB: Upper Bainite, RA: Retained Austenite.

similar to that of our investigations on manganese steel[20] and to those of Pickering[18] and Shackleton and Kelly[30], it differs from that of Bhadeshia and Edmonds[19] who considered that upper bainite and lower bainite form in two separate temperature ranges and have different mechanisms of transformation. The lower bainite formed at 400°C has ferrite with a lath morphology (BIII type according to Ohmori *et al.*[15]).

The martensite formed from untransformed austenite at 450°C and 400°C contained profuse retained austenite films at the interlath boundaries. This suggests that nickel has a much more strong effect on thermal stabilisation of austenite than manganese[20] (as such austenite films were not observed in Mn steel). The importance of these austenite films on the tempered martensite embrittlement has been the subject matter of several earlier researchers[31)-(34].

V. Conclusions

The following conclusions may be drawn on the basis of the present investigation on isothermal transformations of a 0.2%C–3.6%Ni steel.

(1) Transformation at 600°C as well as at 500°C has resulted in the formation of Widmanstätten ferrite/martensite structures which are transitory in nature. Further transformation at 600°C has resulted in the precipitation of cementite as grain boundary allotriomorphs while upper bainite has formed at 500°C.

(2) In view of the above conclusions the ferrite/martensite structures are not considered as bainitic in nature.

(3) Pearlite has not formed even after 10 ks at 600°C suggesting that nickel has strong retarding effect on pearlite formation.

(4) Transformation at 450°C has led to the formation of both upper bainite and lath type lower bainite.

(5) Unlike Mn, nickel has a profound effect in retaining austenite films at the interlath boundary.

Acknowledgements

The authors are grateful to the Head, Department of Metallurgical Engineering, Banaras Hindu University, for providing necessary facilities to carry out the present investigation and to the Defence Research & Development Organisation for financial support.

REFERENCES

(1) E. S. Davenport and E. C. Bain: Trans. AIME, **90** (1930), 117.
(2) V. G. Paranjpe and D. D. Kaushal: Trans. IIM, **5** (1951), 147.
(3) R. F. Heheman and A. R. Troiano: Metals Progress, (1956), 97.
(4) H. I. Aaronson: *The mechanism of phase transformation in crystalline solids*, Inst. Metals Monogr., (1969), 270.
(5) R. F. Heheman: *Phase Transformations*, ASM, Metals Park, Ohio, (1970), p. 397.
(6) H. K. D. H. Bhadeshia and J. W. Christian: Metall. Trans. A, **21A** (1990), 767.
(7) H. I. Aaronson, W. T. Reynolds, Jr., G. J. Shiflet and G. Spanos: Metall. Trans. A, **21A** (1990), 1343.
(8) R. F. Heheman, K. R. Kinsman and H. I. Aaronson: Metall. Trans., **3** (1972), 1077.
(9) A. B. Greninger and A. R. Troiano: Trans. AIME, **140** (1940), 307.
(10) J. R. Vilella: Trans. AIME, **140** (1940), 332.
(11) G. Spanos, H. S. Fang, D. S. Sarma and H. I. Aaronson: Metall. Trans. A, **21A** (1990), 1391.
(12) W. T. Reynolds, Jr., F. Z. Li, C. K. Shui, Q. J. Shiflet and H. I. Aaronson: *Phase Transformations '87*, Institute of Metals, London, (1988), p. 330.
(13) M. Hillert: *Decomposition of Austenite by Diffusional Processes*, Interscience, New York, (1962), p. 197.
(14) K. R. Kinsman and H. I. Aaronson: Metall. Trans., **1** (1970), 1485.
(15) Y. Ohmori, H. Ohtani and T. Kunitake: Trans. ISIJ, **11** (1971), 250.
(16) M. K. Kang, J. L. Sun and Q. M. Yang: Metall. Trans. A, **21A** (1990), 853.
(17) B. L. Bramfitt and J. G. Speer: Metall. Trans. A, **21A** (1990), 817.
(18) F. B. Pickering: *Transformation and Hardenability in Steel*, Climax Molybdenum Co., Ann Arbor, Michigan, (1967), p. 109.
(19) H. K. D. H. Bhadeshia and D. V. Edmonds: Metall. Trans. A, **10A** (1979), 895.
(20) A. Joarder and D. S. Sarma: to be published.
(21) K. W. Andrews, D. J. Dyson and S. R. Keown: *Interpretation of Electron Diffraction Patterns*, Adam Higher, London, (1971).
(22) J. M. Chilton and G. R. Speich: Metall. Trans., **1** (1970), 1019.
(23) P. G. Boswell, K. R. Kinsman, G. J. Shiflet and H. I. Aaronson: *Mechanical Properties and Phase Transformations in Engineering Materials—Eart R. Parker Symposium on Structure Property Relationship*, TMS-AIME, Warrendale, PA, (1986), p. 445.
(24) H. Tsubakino and H. I. Aaronson: Metall. Trans. A, **18A** (1987), 2047.
(25) Yiwen Mou and T. Y. Hsu: Metall. Trans. A, **19A** (1988), 1695.
(26) S. K. Liu and G. Y. Zhang: Metall. Trans. A, **21A** (1990), 1509.
(27) Jye-Long Lee, Min-Hsiung Hon and Gwo-Hwa Cheng: Scripta Metall., **22** (1987), 293.
(28) Jye-Long Lee, Min-Hsiung Hon and Gwo-Hwa Cheng: Scripta Metall., **21** (1987), 521.
(29) W. T. Reynolds Jr., S. K. Liu, F. Z. Li, S. Hartfield and H. I. Aaronson: Metall. Trans. A, **21A** (1990), 1479.
(30) D. N. Shackleton and P. M. Kelly: *Physical Properties of Martensite and Bainite*, The Iron and Steel Institute, Special report, **93** (1956), p. 126.
(31) G. Thomas: Metall. Trans. A, **9A** (1978), 439.
(32) B. V. N. Rao and G. Thomas: Metall. Trans. A, **11A** (1980), 441.
(33) D. S. Sarma: Tool and Alloy Steels, **18** (1984), 363.
(34) R. M. Horn and R. O. Ritchie: Metall. Trans. A, **9A** (1978), 1039.