JOURNAL OF MATERIALS SCIENCE 18 (1983) 2893–2904

The morphology of martensite in Fe–C, Fe–Ni–C and Fe–Cr–C alloys

MINORU UMEMOTO, EIZOH YOSHITAKE,* IMAO TAMURA
Department of Metal Science and Technology, Kyoto University, Yoshida-honmachi, Sakyo-ku, Kyoto 606, Japan

The morphology of martensite in widely varying series of Fe–C, Fe–Ni–C and Fe–Cr–C alloys was investigated using optical microscopy. The effects of formation temperature and alloying elements on the martensite morphology were studied in detail. It was found that in Fe–C alloys, lath martensite forms in alloys with less than 0.8 wt % carbon, butterfly martensite forms in alloys with between 0.98 and 1.42 wt % carbon and lenticular martensite forms in alloys with more than 1.56 wt % carbon. In Fe–Ni–C alloys, four different martensite morphologies form depending upon the formation temperature and composition, and for alloys of a fixed carbon content the martensite morphology changes from lath to butterfly to lenticular to thin plate as the formation temperature is decreased. In Fe–Cr–C alloys, lath martensite forms at high temperature, and below the lath formation temperature mainly $\{2\,2\,5\}_f$ plate martensite is formed. Based on the results obtained, the importance of the strength of austenite, and the austenite stacking fault energy to the martensite morphology was discussed.

1. Introduction

In ferrous alloys various martensite morphologies have been recognized. For instance, Fig. 1 shows four different morphologies of bcc (or bct) martensites observed in Fe–Ni–C alloys. These are called (a) lath, (b) butterfly, (c) lenticular and (d) thin plate martensite, respectively. These martensites are distinguished not only morphologies but also crystallographically. According to previous studies, lath martensite exhibits a near $\{1\,1\,1\}_f$ habit and contains a high dislocation density [1–3]. Butterfly martensite exhibits a $\{2\,2\,5\}_f$ habit, contains several kinds of defects other than $\{1\,1\,2\}_b$ transformation twins and some but not all plates show mid-ribs [4, 5]. Lenticular martensite exhibits a $\{2\,5\,9\}_f$ or $\{3, 10, 15\}_f$ habit and is partially twinned with a mid-rib [1, 6–8]. Thin plate martensite exhibits a $\{3\;10\;15\}_f$ habit and is completely twinned without a mid-rib [9–11]. Other than these four morphologies, plate-like martensite with a $\{2\,2\,5\}_f$ habit has been observed in some ferrous alloys such as Fe–Cr–C [12, 13], Fe–Cr–Mn–C [14] and Fe–Mn–C [15].

It is also known that martensite morphology in ferrous alloys is strongly related to the mechanical properties of materials and thus an understanding of the formation conditions of these martensite morphologies is of considerable importance. The purpose of the present study was to investigate the morphology of the martensite forms found in Fe–C, Fe–Ni–C and Fe–Cr–C alloys and observe the effect of alloying elements on the martensite morphology. Special attention was paid to the martensite with the $\{2\,2\,5\}_f$ habit. The possible factors controlling martensite morphology were discussed in view of the results obtained in the present investigation.

2. Experimental procedure

The alloys used in the present study were prepared by vacuum induction melting, and two commercial steels. Their chemical compositions are listed in Table I. Specimens were austenitized at 1423 K

---

*Present address: Department of Materials Science, Northwestern University, Evanston, Illinois 60201, USA.

0022–2461/83 $03.00 + .12

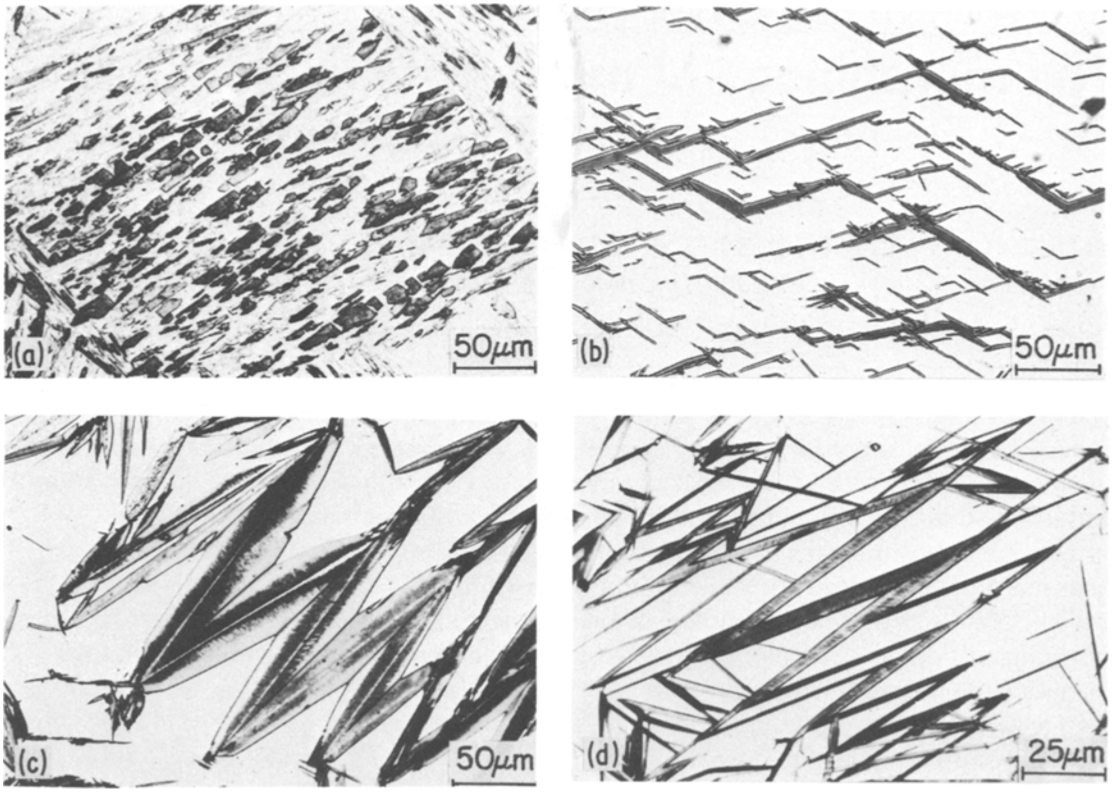

Figure 1 Optical micrographs showing different morphologies of martensites formed in Fe–Ni–C alloys. (a) Lath martensite in an Fe–15Ni–0.24C alloy. (b) Butterfly martensite in an Fe–20Ni–0.73C alloy. (c) Lenticular martensite in an Fe–31Ni–0.23C. (d) Thin plate martensite in an Fe–31Ni–0.29C.

for 1.8 ksec in vacuo and quenched in a salt bath (or oil bath) kept at a temperature T_1 (just below M_s) to obtain a small amount (a few %) of martensite, where M_s is a martensite start temperature. Specimens were then quenched up in a salt bath kept at 523 K (for the specimens whose M_s temperature is above 523 K, specimens were quenched up about 40 K above the M_s temperature) held for 5 to 60 sec and then water quenched. With this up-quenching treatment, the martensites formed at T_1 were tempered and sensitized to the following etching. Such a tempering technique used to observe the martensite structure formed above room temperature is called the Greninger–Troiano

TABLE I Chemical compositions

Specimen	Elements present (wt%)										M_s (K)
	C	Si	Mn	P	S	Cu	Ni	Cr	Mo	Fe	
Fe–0.60C	0.60	0.23	0.49	0.017	0.012	–	–	–	–	Bal	623
Fe–0.98C	0.98	0.26	0.16	0.007	0.006	0.01	0.01	0.03	0.01	Bal	463
Fe–1.42C	1.42	0.01	0.01	0.004	0.01	–	–	–	–	Bal	383
Fe–1.56C	1.56	0.14	0.33	0.004	0.005	–	–	0.03	–	Bal	353
Fe–2.07C	2.07	0.34	0.33	0.004	0.005	–	–	0.03	–	Bal	283
Fe–8Ni–1.26C	1.26	0.010	0.002	0.006	0.015	–	7.55	–	–	Bal	203
Fe–12Ni–1.06C	1.06	0.002	0.003	0.004	0.004	–	12.0	–	–	Bal	243
Fe–15Ni–0.24C	0.24	0.008	0.002	0.002	0.005	–	14.74	–	–	Bal	453
Fe–20Ni–0.73C	0.73	0.003	0.005	0.004	0.004	–	19.50	–	–	Bal	273
Fe–25Ni–0.37C	0.37	0.04	0.005	0.003	0.002	–	25.21	–	–	Bal	234
Fe–1C4–1.50C	1.50	0.003	0.002	0.003	0.005	–	–	1.07	–	Bal	333
Fe–3Cr–1.44C	1.44	0.004	0.001	0.003	0.004	–	–	2.92	–	Bal	273
Fe–8Cr–0.92C	0.92	0.008	0.002	0.004	0.003	–	–	7.78	–	Bal	323

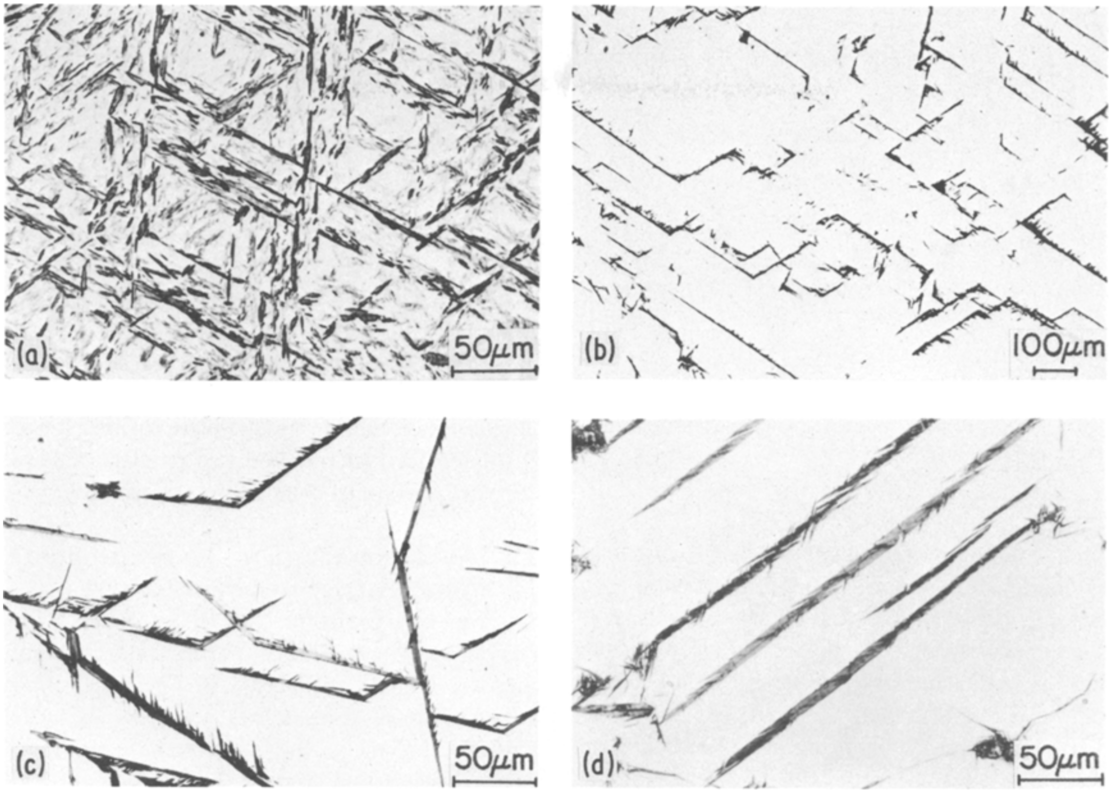

Figure 2 Optical micrographs showing morphologies of martensites formed in Fe–C alloys with various carbon content. (a) Fe–0.60C steel cooled to 528 K. (b) Fe–0.98C steel cooled to 453 K. (c) Fe–1.42C alloy cooled to 373 K. (d) Fe–2.07C alloy cooled to 273 K.

(G–T) heat treatment [1]. After these heat treatments specimens were polished mechanically and chemically and etched either with 2% nital, 5% nital or 35% aqueous sodium bisulphite solution prior to the optical microscope observation.

A group of specimens were austenitized at 1423 K for about 1.2 to 7.2 ksec in a gaseous atmosphere (10% H_2 and 90% N_2) to produce a decarburized layer. Specimens were then quenched to temperature T_1 to form martensite in the decarburized layer within a certain depth from the surface. When the temperature T_1 is above room temperature, specimens were tempered and then water quenched. After these thermal treatments, specimens were mechanically and chemically polished. Optical microscope observation was carried out after etching using the solutions mentioned above.

3. Experimental results

3.1. Morphology of martensite in Fe–C alloys

Fig. 2 shows optical micrographs of martensites formed in Fe–C alloys with various carbon contents. It is seen that lath martensite forms in the Fe–0.60C alloy (a), butterfly martensite forms both in the Fe–0.98C steel (b) and the Fe–1.42C alloy (c) and lenticular martensite forms in the Fe–2.07C alloy (d). According to previous studies [1, 16–18], lath martensite with a $\{1\,1\,1\}_f$ habit forms in alloys containing less than 0.6 wt% carbon, plate martensite with a $\{2\,2\,5\}_f$ habit forms in alloys containing 1.0 to 1.4 wt% carbon and plate martensite with a $\{2\,5\,9\}_f$ habit forms in alloys containing 1.8 wt% carbon. However, in the present study butterfly martensites were observed in the Fe–0.98C steel and the Fe–1.42C alloy. This indicates that Fe–C martensite with a $\{2\,2\,5\}_f$ habit is butterfly martensite and can be distinguished morphologically from lenticular martensite with a $\{2\,5\,9\}_f$ or a $\{3\,10\,15\}_f$ habit.

The morphology of martensite formed in an Fe–1.56C alloy is somewhat different from that of the commonly observed lenticular martensite. Fig. 3 shows martensite formed in an Fe–1.56C alloy at 343 K. An array of 'V'-shapes, each of

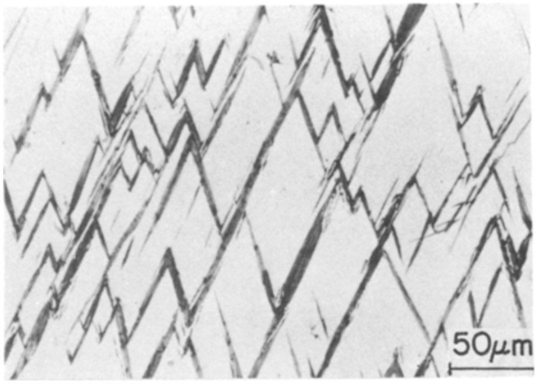

Figure 3 Optical micrograph showing martensite formed in an Fe–1.56C alloy cooled to 343 K.

which consists of two relatively small lenticular-like martensites, is seen. A mid-rib exists in each plate. However, the size of the martensite is smaller and the junction plane is shorter and more obscure than the lenticular martensite observed in Fe–Ni–C alloys with a high nickel content. The Fe–1.56C alloy has an intermediate carbon content between those alloys which form a $\{2\,2\,5\}_f$ habit and a $\{2\,5\,9\}_f$ habit [1]. Thus it is possible that the habit plane of the martensite formed in the Fe–1.56C alloy is inbetween $\{2\,2\,5\}_f$ and $\{2\,5\,9\}_f$ and their morphology might be a unique one to these martensites.

Our previous investigation [4] revealed that there are two types (called type A and B) of butterfly martensite: type A is characterized by thin wings, smooth and straight austenite–martensite interfaces and without a mid-rib, while type B is characterized by thicker wings and an existance of a mid-rib. In the present study both type A and B butterfly martensites were observed in the Fe–C alloys but some differences were observed between Fe–Ni–C and Fe–C alloys especially in type B butterfly martensite.

Fig. 4 shows a comparison of type B butterfly martensite formed in the two alloy systems. Fig. 4a shows the butterfly martensite formed in the Fe–1.42C alloy at 373 K and (b) shows the one formed in an Fe–18Ni–0.7Cr–0.5C alloy at 263 K. It should be noted that a mid-rib exists in both alloys but many branches are observed only in the Fe–C butterfly martensite. These branches are parallel to each other in a given plate and parallel to another martensite plate forming a pair. This indicates that the branched part and martensite plate is a special combination of variants.

3.2. Morphological transition temperature from butterfly to lath martensite in Fe–Ni–C alloys

The morphological transition temperature from butterfly to lath martensite in Fe–Ni–C alloys was determined using alloys with various nickel contents. To make the experiment easy, specimens whose carbon content is a function of depth from the surface were produced by applying an appropriate decarburization. After decarburization (which was also an austenitizing treatment) specimens were cooled to various temperatures to transform them to martensite with a certain depth in the decarburized layer, which is followed by the G–T treatment. Specimens were then mechanically polished, changing the polished depth from one end to another (with one end deep and the other end shallow). The new surface exhibits regions with varying degrees of decarburization. Polishing was carried out until the new surface exhibited

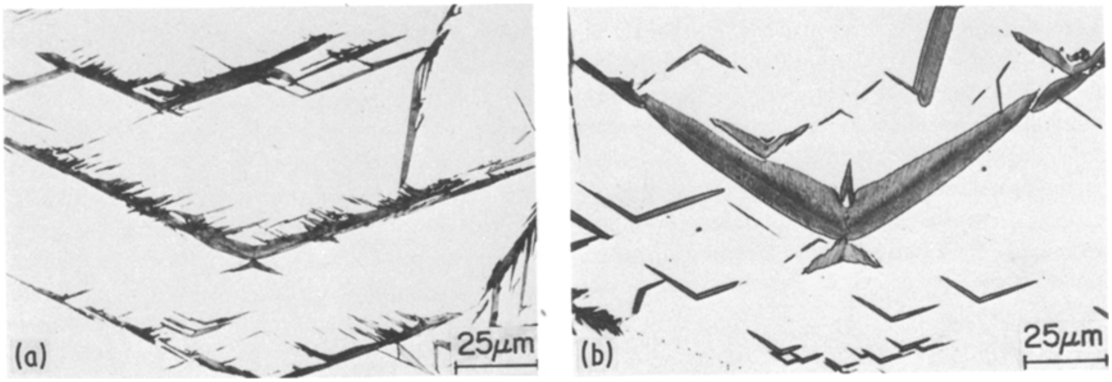

Figure 4 Optical micrograph showing type B butterfly martensites observed (a) in an Fe–1.42C alloy cooled to 373 K and (b) in an Fe–18Ni–0.7Cr–0.50C alloy cooled to 263 K.

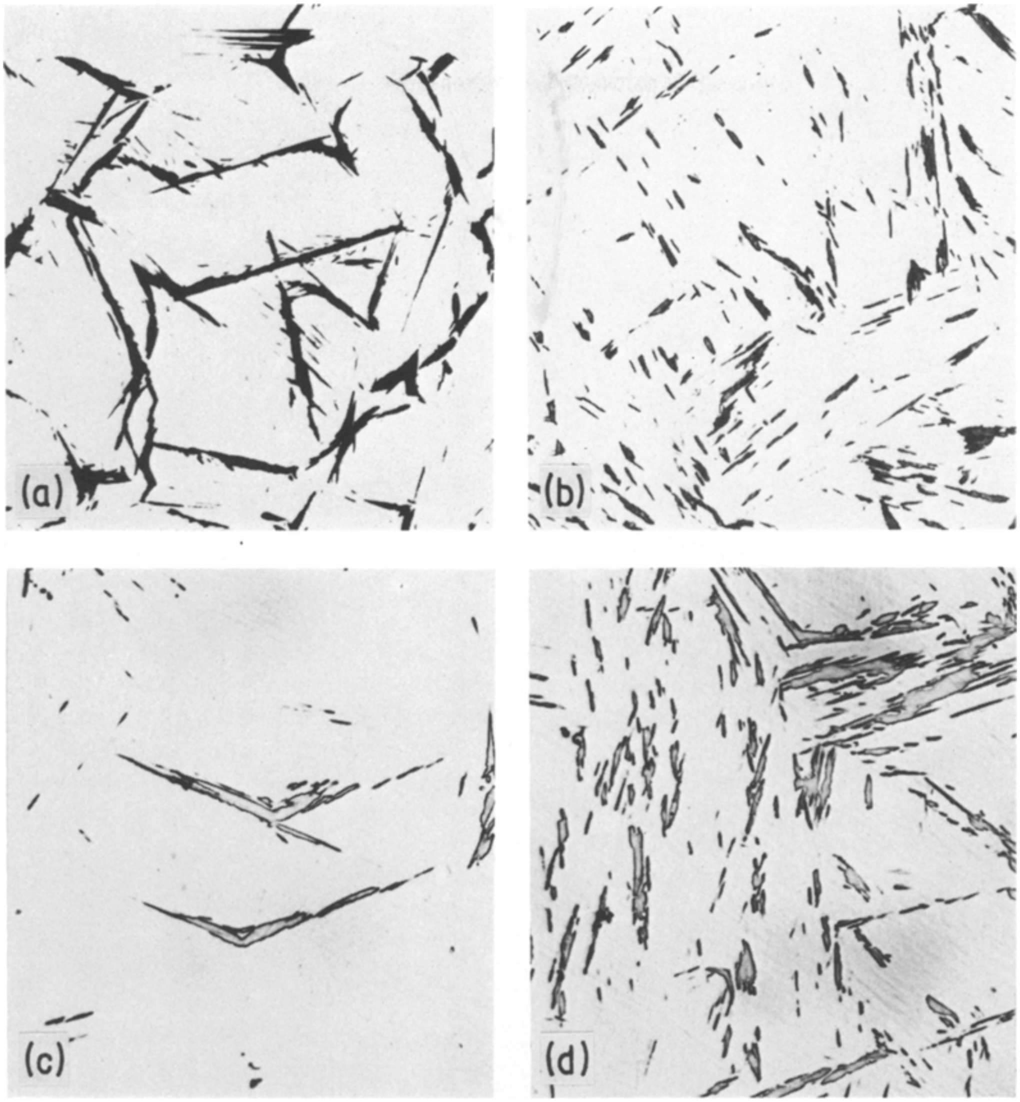

Figure 5 Optical micrographs showing the morphological transition from lath to butterfly martensite in Fe–Ni–C alloys. Martensites observed were formed in a decarburized layer of the specimens. (a) and (b) were taken from an alloy containing 12%Ni and the martensites were formed at 423 and 443 K, respectively. (c) and (d) were taken from an alloy containing 20%Ni and the martensites were formed at 383 and 395 K, respectively. (e) and (f) were taken from an alloy containing 25%Ni and martensites were formed at 323 and 343 K, respectively.

100% martensite (tempered and sensitized to the etching) at one end and 0% at the other end. The martensite formed at temperature T_1 was recognized where the smallest amount of martensite was observed. A part of the present results are summarized in Fig. 5. Fig. 5a and b are martensites formed in the specimens containing 12 wt% Ni (Fe–12Ni–1.06C before decarburization). As is seen, butterfly martensite forms at the region where M_s is raised up to 423 K by decarburization while lath martensite forms at the region where M_s becomes higher than 443 K by further decarburization. In the alloy containing 20 wt% Ni (Fe–20Ni–0.73C before decarburization) butterfly martensite (see Fig. 5c) forms at the region where M_s is raised up to 383 K by decarburization and lath martensite is observed at the region where M_s becomes higher than 395 K (see Fig. 5d). In the alloy containing 25 wt% Ni (Fe–25Ni–0.37C before decarburization), butterfly martensite forms at the region where M_s is raised up to 323 K (see Fig. 5e) and lath martensite is observed at the

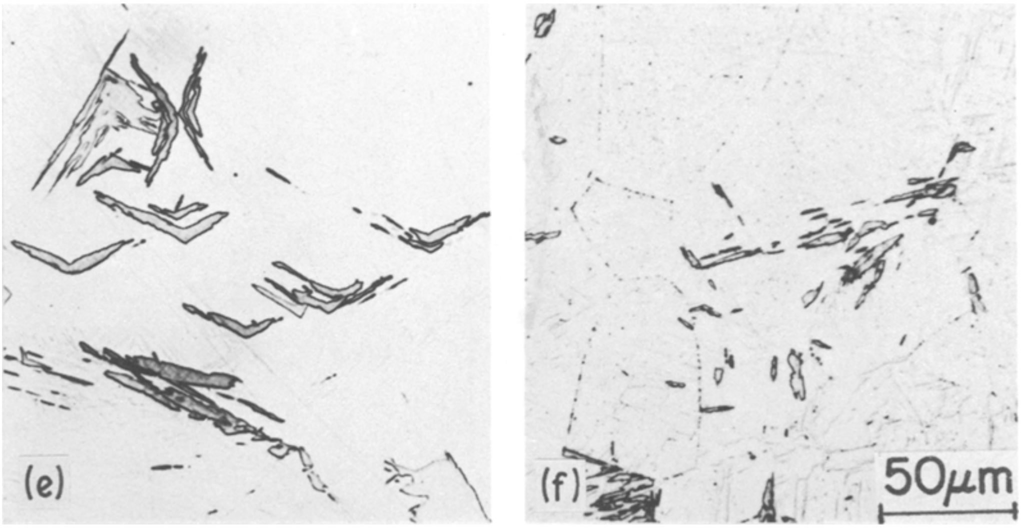

Figure 5 Continued

region where M_s becomes above 343 K (see Fig. 5f). These observations clearly indicate that in Fe–Ni–C alloys the morphological transition temperature from butterfly to lath martensite decreases markedly with an increase in the nickel content.

3.3. Morphology of martensite in Fe–Ni–C alloys and its dependence on the formation temperature and carbon content

Fig. 6 shows a graphical summary of the present observations relating the alloys to martensite morphology as a function of M_s temperature and carbon content. Each alloy is shown here as a point plotted at the formation temperature and carbon content and the marks indicate the main morphology observed. Marks with an asterisk correspond to results from non-decarburized specimens and marks without an asterisk indicate the morphology from decarburized specimens. The results below room temperature are those of previous investigations [19, 20]. From this diagram it can be seen that in the alloys of a fixed carbon content, the martensite morphology changes from lath to butterfly to lenticular to thin plate as the formation temperature is decreased with the increase in nickel content. The transition temperature from lath to butterfly increases markedly with an increase in the carbon content, i.e. from 293 K for a carbon free alloy (Fe–Ni alloy) to about 513 K for 0.8 wt% carbon alloy (Fe–C alloy). While the morphological transition temperature from butterfly to lenticular increases gradually with increasing carbon content from 273 K for a carbon free alloy to about 353 K at 1.5 wt% carbon alloy. (Here the array of V-shaped martensite formed in Fe–1.56C alloy at 343 K was classified as a lenticular martensite.)

3.4. Morphology of martensite in Fe–Cr–C alloys

Although several studies on the morphologies of martensite in Fe–Cr–C alloys have been reported [12, 13, 21, 22], no systematic studies of the effect of formation temperature or chromium content on martensite morphology has been made. The morphology of martensite formed in Fe–Cr–C alloys is of special interest because chromium is one of the typical elements which reduce the stacking fault energy (SFE) of austenite in contrast with nickel. In the present study, martensite morphologies formed in various Fe–Cr–C alloys were investigated.

Fig. 7a shows the martensite formed in an Fe–3Cr–1.44C alloys at 263 K. An array of V-shapes each of which consists of two small lenticular plates were observed. This martensite morphology is quite similar to that observed in the Fe–1.56C alloy and different from the common lenticular martensite plate which usually extends from one grain boundary to another, exhibiting a zig-zag pattern. Using Fe–Cr–C alloys of similar compositions Otte and Read [21] and Johnson and Wayman [22] determined the habit plane. They

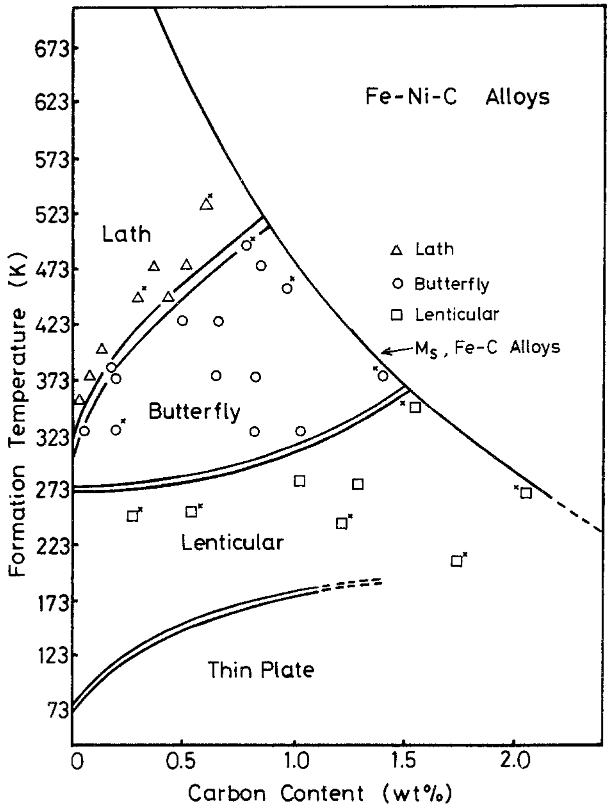

Figure 6 The morphology of Fe–Ni–C martensite presented as a function of the formation temperature and the carbon content. The asterisk indicates non-decarburized specimens.

both reported that the habit plane poles were not close to either $\{2\,2\,5\}_f$ or $\{2\,5\,9\}_f$ but lie in between these two poles. Therefore, the martensite morphology shown in Fig. 7a is possibly a unique form of the martensite with a habit plane poles in between $\{2\,2\,5\}_f$ and $\{2\,5\,9\}_f$.

Fig. 7b shows martensite formed in an Fe–8Cr–0.92C alloy at 303 K. Long thin martensite plates extend from one grain boundary to another are seen but they do not form a zig-zag pattern like lenticular martensite. According to Morton and Wayman [12] and Shimizu *et al.* [13], the habit plane orientation of this martensite morphology is close to $\{2\,2\,5\}_f$ and the martensite plate exhibits several kinds of internal defects such as $\{1\,1\,2\}_b$ transformation twins, $\{1\,1\,0\}_b$ type planar defects and lengthy dislocations. This type of martensite has also been observed in some other ferrous alloys such as Fe–Cr–Mn–C [14] or Fe–Mn–C [15] and is called the $\{2\,2\,5\}_f$ plate martensite.

The morphology of $\{2\,2\,5\}_f$ plate martensite

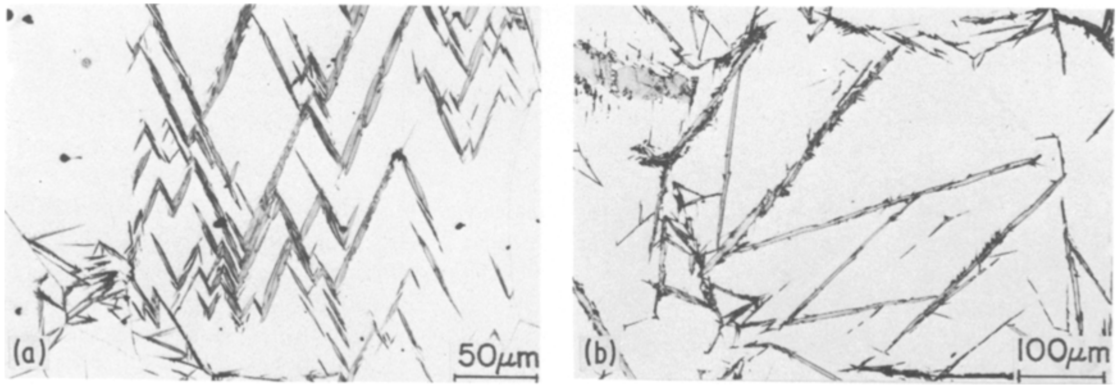

Figure 7 Optical micrographs showing martensite morphologies formed in Fe–Cr–C alloys. (a) Fe–3Cr–1.44C cooled to 263 K. (b) Fe–8Cr–0.92C cooled to 303 K.

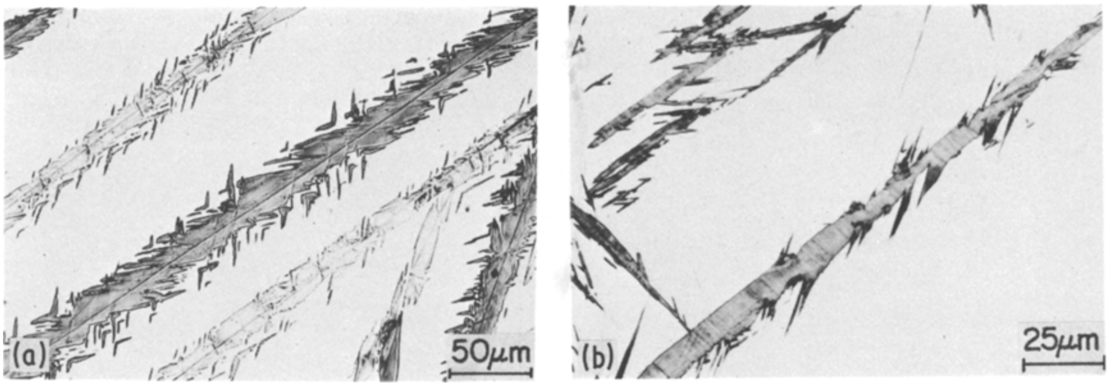

Figure 8 Comparison of lenticular martensite and $\{225\}_f$ plate martensite. (a) Lenticular martensite formed in an Fe–23Ni–0.26C alloy at 273 K. (b) $\{225\}_f$ plate martensite formed in an Fe–8Cr–0.92C alloy at 303 K.

sometimes appears similar to that of lenticular martensite formed at relatively high temperature. Fig. 8 shows a comparison of these two morphologies. Fig. 8a shows a lenticular martensite formed in an Fe–23Ni–0.26C alloy at 273 K and Fig. 8b shows a $\{225\}_f$ plate martensite formed in an Fe–8Cr–0.92C alloy at 303 K. Both martensites exhibit long thin plate shapes and a midrib. However, the lenticular martensite is accompanied with many butterfly martensites of the same group along the plate. The longitudinal directions of the two wings of butterfly martensite (traces of $\{225\}_f$) are not parallel to the direction of the mid-rib of lenticular martensite (trace of $\{259\}_f$). On the other hand $\{225\}_f$ plate martensite exhibits one-directional branching as is seen in Fig. 8b. In general, martensite plate with a $\{225\}_f$ habit tends to form a pair with a special variant and the branching shown in Fig. 8b is considered to be one of these pairs. As a whole, lenticular martensite is accompanied with butterfly martensite along the plate and $\{225\}_f$ plate martensite exhibits one-directional branching. Thus these two morphologies can be distinguished with a conventional optical microscope.

3.5. The effects of formation temperature and alloying elements on the morphology of martensite in Fe–C, Fe–Ni–C and Fe–Cr–C alloys

In the present study the morphology of martensite formed in Fe–C, Fe–Ni–C and Fe–Cr–C alloys were observed. The results are summarized as a function of alloying elements and formation temperature as shown in Fig. 9. In the figure the vertical axis corresponds to the pure Fe–C alloys

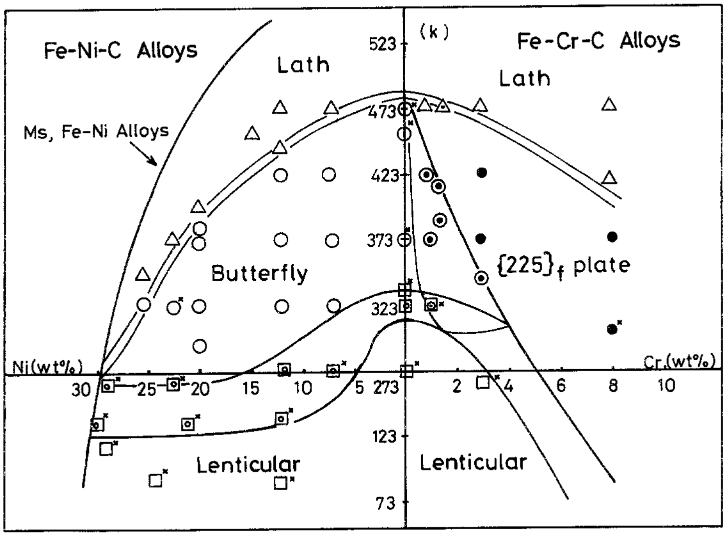

Figure 9 The morphology of martensite formed in Fe–Ni–C and Fe–Cr–C alloys presented as a function of the formation temperature and content of alloying elements. △ lath, ○ butterfly, ● $\{225\}_f$ plate, ⊙ butterfly and $\{225\}_f$ plate, □ lenticular, ▣ butterfly and lenticular, ⊡ butterfly, $\{225\}_f$ plate and lenticular. The asterisk represents non-decarburized specimens.

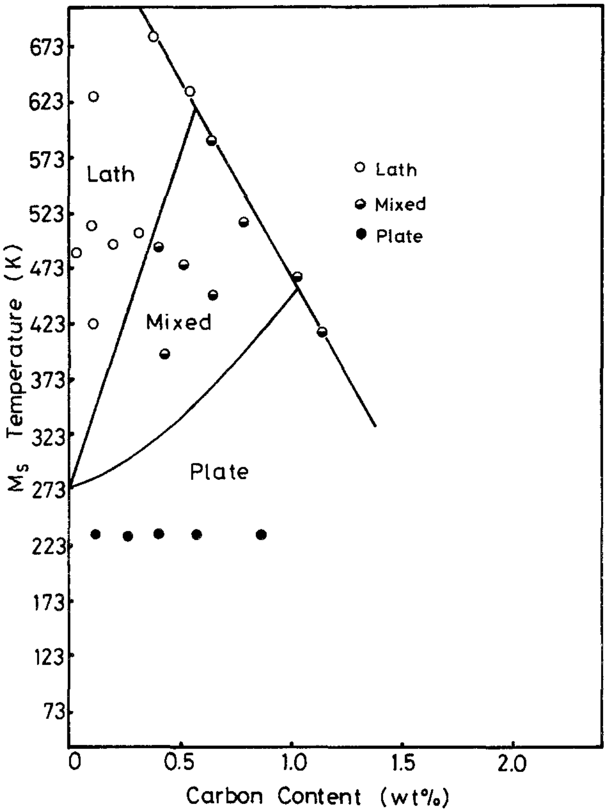

Figure 10 Structural results of martensite for Fe–Ni–C alloys reported by Magee and Davis [23].

and left and right hand sides from this line correspond to Fe–Ni–C and Fe–Cr–C alloys, respectively. The marks with an asterisk indicate results obtained from the non-decarburized specimens and the marks without an asterisk indicate those obtained from decarburized specimens. (Here the so called $\{225\}_f$ plate martensites were recognized from the morphological similarities with those formed in an Fe–8Cr–0.92C alloy. The measurement of habit planes were not carried out in the present study.) From this diagram the following points can be seen. In all the alloys studied, lath martensite forms at high temperatures, lenticular martensite forms at low temperatures and at an intermediate temperature range martensite with a $\{225\}_f$ habit forms. The lower temperature limit of the lath formation decreases with increase in either nickel or chromium content. Below the lath formation temperature, butterfly martensite forms in Fe–Ni–C alloys while mostly $\{225\}_f$ plate martensite forms in Fe–Cr–C alloys.

As is shown above, an addition of either nickel or chromium to Fe–C alloys changes the habit plane of martensite from near $\{111\}_f$ to $\{225\}_f$. This indicates that the effect of austenite SFE on the transition of a habit plane from $\{111\}_f$ to $\{225\}_f$ may be small. However, the chromium addition drastically changes the martensite morphology, that is, at the temperature range between 373 and 423 K only butterfly martensite forms in Fe–C alloys but $\{225\}_f$ plate martensite is predominant in alloys containing more than 1 wt % Cr. This indicates that the effect of austenite SFE may be large on determining the morphology of martensite with $\{225\}_f$ habit.

4. Discussions

4.1. The martensite morphology in Fe–Ni–C alloys

A number of investigations on the morphology of ferrous martensite have been reported. However, systematic studies on the effect of alloying elements on the martensite morphology are limited. Magee and Davies [23] observed martensite morphologies formed in a widely varying series of Fe–Ni–C alloys and summarized the results as a function of M_s temperature and carbon content as is shown in Fig. 10. They classified the martensite morphology into lath and plate and showed temperature ranges at which either lath or plate martensite or a mixture of the two morphologies forms.

There are several differences between the figure they reported (Fig. 10) and the figure obtained in the present study (Fig. 6). One is the classification of martensite morphologies. Magee and Davies classified martensite morphologies into lath and plate martensite but in the present study the so called plate morphology is further classified into 3 types, i.e. butterfly, lenticular and thin plate. The second is the relation between the martensite morphology and temperature. In the present study the martensite formed just below M_s temperatures were observed using G–T heat treatment. Thus the vertical axis of Fig. 6 indicates the formation temperature of martensite. On the other hand, Magee and Davies observed the martensite structure after cooling to room temperature. Thus although the vertical axis of Fig. 10 indicates the M_s temperature of the specimens, the points in the figure indicate the martensite structure formed at all the temperatures between M_s and M_f or room temperature, where M_f is a martensite finish temperature. Therefore these two figures are constructed in somewhat different ways and cannot directly be compared. However, one can see from Fig. 6 that if the specimen with a M_s temperature just above the morphological transition from lath to butterfly martensite is cooled to room temperature, the structure obtained will be a mixture of lath and butterfly martensites. Thus it is understandable why the mixed region exists in Fig. 10.

4.2.1. The factors controlling the martensite morphology

There have been many discussion on the factors controlling the martensite morphology. The factors proposed so far are;

(a) M_s temperature [3, 24, 25]

(b) austenite stacking fault energy [7]

(c) driving force associated with the transformation [26, 27]

(d) the strength of martensite and austenite [28]

(e) critical resolved shear stress for slip and twinning in martensite [29, 30].

In most of the cases these factors are related to each other and it is quite difficult to investigate the effect of one single factor on the martensite morphology. Therefore no general agreements have been obtained yet.

At what stage of transformation is the martensite morphology determined? Although not much is known about the nucleation mechanism of martensite, it is hard to imagine that there exist different structures of nuclei corresponding to different morphologies of martensite. It is more likely that the structure of the nuclei is the same for every martensite morphology and the morphology will be determined during the growth process. In more realistic terms martensite morphology will be determined by the minimization of the plastic work for the lattice invariant shear in the austenite and martensite phases. If this is so, the strength of austenite and martensite at the M_s temperature is considered to play a most important role in controlling the martensite morphology. The strength of martensite should be the strength of ferrite (over saturated solid solution of C, N etc) of the same composition with the parent phase and without lattice defects observed in fully grown martensite. However the strength of the ferrite is generally hard to estimate. On the other hand the strength of austenite at M_s temperature is relatively easy to obtain. Thus the interrelation between the strength of austenite and martensite morphology in Fe–Ni–C alloys was examined.

The strength of austenite was calculated considering the carbon content and temperature. Since the solid solution hardening of austenite by nickel atom is very small [31], the influence of the nickel content on the austenite strength was ignored. The effects of carbon on the flow stress of austenite in Fe–Ni–C alloys have been well studied by Bolling and Richman [32]. According to their experimental results the austenite flow stress at a strain of 10^{-3} (measured by tensile tests with a strain rate $3 \times 10^{-5}\,\text{sec}^{-1}$) and at a temperature of 420 K is approximately given as

$$\sigma = 195.0 \times (\text{wt}\,\%\text{C}) + 76.4 \qquad (1)$$

where σ is in MPa mm^{-2}.

The effects of temperature on the austenite strength depends on the magnetic character, i.e. whether the austenite is ferromagnetic or paramagnetic. In Fe–Ni–C alloys, except at very low temperature, martensite forms from paramagnetic austenite. Thus here only the austenite strength in the paramagnetic range will be considered. According to Bolling and Richman [32], the temperature dependence of paramagnetic austenite strength (at a strain of 0.1%) can be expresses as

$$\frac{\partial \sigma}{\partial T} = 2.53 \times (\text{wt}\%\text{C}) + 0.20. \qquad (2)$$

From Equations 1 and 2, the relationship between the temperature and carbon content which results in an equal austenite strength, can be

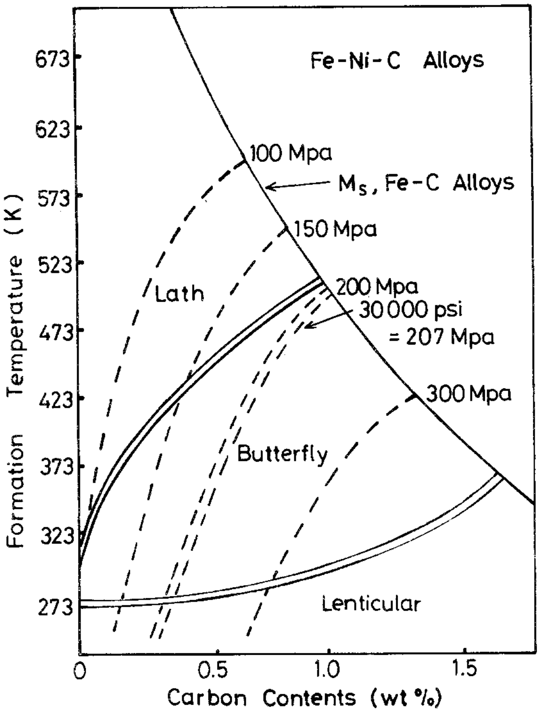

Figure 11 Comparison of the strength of austenite calculated from the data reported by Bolling and Richman [32] with the morphological transition curves obtained in the present study.

obtained. Fig. 11 shows such relationships for austenite strength of 100, 150, 200 and 300 MPa mm^{-2}. Comparing these curves with the morphological transition curves in Fig. 6, the line of equal strength of austenite is relatively close to the morphological transition from lath to butterfly martensite but not close to the morphological transition curve from butterfly to lenticular martensite. This indicates that the strength of austenite may play an important role in the morphological transition from lath to butterfly but not to that from butterfly to lenticular martensite.

Davies and Magee [28] have measured the austenite strength at the M_s temperature in various ferrous alloys and concluded that when the austenite strength is larger than 206.7 MPa (30,000 psi), the lenticular martensite with a $\{259\}_f$ habit forms irrespective of the strength of the martensite. However, Fig. 11 shows that this statement does not hold for all the Fe–Ni–C alloys, and for the formation of lenticular martensite some other factors (possibly the stacking fault energy of austenite) is working at the same time.

5. Summary

The effects of formation temperature and alloying elements on the martensite morphologies, mainly those with $\{225\}_f$ habit, were studied using Fe–C, Fe–Ni–C and Fe–Cr–C alloys. The main results obtained were as follows.

1. In Fe–C alloys at M_s temperatures lath martensite forms in alloys containing less than 0.8 wt% carbon, butterfly martensite forms in alloys containing between 0.98 and 1.42 wt% carbon and in alloys containing more than 1.56 wt% carbon lenticular martensite forms.
2. Butterfly martensite formed in Fe–C alloys exhibits much one-directional branching on each wing and these branches are parallel to other plates.
3. In Fe–Ni–C alloys four different morphologies of martensite form depending upon the formation temperature and composition. For alloys of a fixed carbon content the martensite morphology changes from lath to butterfly to lenticular to thin plate as the formation temperature is decreased.
4. The morphological transition temperature from lath to butterfly martensite increases markedly with increase in carbon content from 293 to 513 K, while the morphological transition temperature from butterfly to lenticular or lenticular to thin plate martensite increases gradually with increase in carbon content.
5. In Fe–Cr–C alloys lath martensite forms at high temperatures: below the lath formation temperature mostly $\{225\}_f$ plate martensite forms. The butterfly martensite is observed only in alloys with a Cr content less than 1 wt%.
6. The austenite SFE may play an important role in controlling the martensite morphology, i.e. whether it is butterfly or $\{225\}_f$ plate martensite.
7. In Fe–Ni–C alloys the morphological transition from lath to lenticular martensite occurs nearly the same austenite strength over a wide range of temperature and carbon content.

References

1. A. B. GRENIGER and A. R. TROIANO, *Trans. ASM* **140** (1940) 307.
2. A. R. MARDER and G. KRAUSS, *ibid.* **62** (1969) 957.
3. G. KRAUSS and A. R. MARDER, *Met. Trans.* **2** (1971) 2343.
4. M. UMEMOTO and I. TAMURA, Proceedings of the ICOMAT-79 conference Cambridge, Mass. USA, June 1979, p. 53.
5. *Idem.*, Proceedings of the ICOMAT-82 conference

Leuven, Belgium, August 1982. Les éditions de physique.

6. E. S. MACHLIN and M. COHEN, *Trans. AIME* **191** (1951) 1019.
7. P. M. KELLY and J. NUTTING, *J. Iron Steel Inst.* **197** (1961) 199.
8. Z. NISHIYAMA and K. SHIMIZU, *Acta. Metall.* **9** (1961) 980.
9. A. B. GRENINGER and A. R. TROIANO, *Trans. AIME* **145** (1941) 289.
10. T. MAKI, S. SHIMOOKA, M. UMEMOTO and I. TAMURA, *Trans. JIM* **13** (1972) 400.
11. I. TAMURA, Proceedings of the ICOMAT-76 conference, Kobe, Japan, May 1976 (The Japan Institute of Metals) p. 59.
12. A. J. MORTON and C. M. WAYMAN, *Acta Metall.* **14** (1966) 1567.
13. K. SHIMIZU, M. OKA and C. M. WAYMAN, *ibid.* **19** (1971) 1.
14. S. JANA and C. M. WAYMAN, *Met. Trans.* **1** (1970) 2815, 2825.
15. Y. TANAKA and K. SHIMIZU, *Trans. JIM* **21** (1980) 34.
16. A. B. GRENINGER and A. R. TROIANO, *Trans. ASM* **140** (1940) 537.
17. A. R. MARDER and G. KRAUSS, *ibid.* **60** (1967) 651.
18. *Idem, ibid* **62** (1969) 957.
19. T. MAKI, S. SHIMOOKA, S. FUJIWARA and I. TAMURA, *Trans, JIM* **16** (1975) 35.
20. M. UMEMOTO, Y. WATAI and I. TAMURA, *J. Jpn. Inst. Met.* **44** (1980) 453.
21. H. M. OTTE and T. A. READ, *J. Met.* **9** (1957) 412.
22. K. A. JOHNSON and C. M. WAYMAN, *Acta Crystallogr.* **16** (1963) 480.
23. C. L. MAGEE and R. G. DAVIES, *Acta Metall.* **19** (1971) 345.
24. P. M. KELLY and J. NUTTING, *Proc. Roy. Soc. London (a)* **259** (1960) 45.
25. O. JOHARI and G. THOMAS, *Acta Metall.* **13** (1965) 1211.
26. T. BELL and W. S. OWEN, *Trans. AIME* **239** (1967) 1940.
27. J. S. PASSCOVER and S. V. RADCLIFFE, *ibid.* **242** (1968) 673.
28. R. G. DAVIES and C. L. MAGEE, *Met. Trans.* **2** (1971) 1939.
29. K. S. DAS and G. THOMAS, *ibid.* **1** (1970) 325.
30. G. THOMAS, *ibid.* **2** (1971) 2373.
31. D. J. DYSON and B. HOLMES, *J. Iron Steel Inst.* **208** (1970) 469.
32. G. F. BOLLING and R. H. RICHAMN, *Acta Metall.* **18** (1970) 673.

Received 25 October 1982
and accepted 5 January 1983