

Exploring on Stereo Morphology and Habit Plane of Martensite in Ferrous Alloy

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Abstract. Themicrostructures of 20, 30, 40, 45, T9, T10, T11, 20Cr, 40Cr, 45CrNi, 65Mn, 9CrSi, CrWMn commercial carbon and alloy steels were observed by optical microscopy, scanning electron microscopy and transmission election microscopy, meanwhile the habit plane, the substructure and stereo shapeof martensit have been proposed. It was verified that the packet martensite should be divided into packet thin sheet martensite and packet fine martensite, the latter principally can be divided into {557}A packet fine plate martensite, {1 1 1}A packet fine plate martensite and {2 2 5}A packet fine plate martensite according to the carbon content. Space morphology of low carbon packet martensite units is sheet-like but not lath-like; that of martensite medium and high carbon packet martensite units is plate-like. There is no noticeable difference between the substructures of lath and plate martensite. Martensite without internal twin is not certainly lath martensite, while all martensite with numerous internal twins is certainly plate martensite.

1. Introduction

Since the substructure of martensite were observed by using transmission electron microscopy (TEM) firstly in 1960s [1], the understanding about martensite has been developed obviously, but there are many controversial conclusions, even mutual discrepancy, in the available research data concerning the fundamental feature and behaviour of martensite.

However, the type of martensite, the three-dimensional morphology of martensite units, the crystallographic relationship, the habit plane, the orientation relationship between martensite units, the role of austenitizing temperature on type of martensite, etc. were all kept to be controversial.

To explore the basic rulesunderlying such contradictions, especially characters of lath and plate matensite, series carbon and alloy steels were utilized to clarify the such ambiguities mentioned above.

2. Materials and procedures

The chemical compositions of steels tested are listed in Table 1.



Table 1. Chemical compositions of steel tested, (wt %)

| Steel | C | Mn | Si | Cr | Ni | W |
|--------|------|------|------|------|------|------|
| 10 | 0.11 | 0.56 | 0.23 | - | - | - |
| 20 | 0.19 | 0.70 | 0.25 | - | - | - |
| 20Cr | 0.21 | 0.74 | 0.32 | 0.99 | - | - |
| 40 | 0.38 | 0.65 | 0.21 | - | - | - |
| 40Cr | 0.43 | 0.66 | 0.35 | 0.95 | - | - |
| 45 | 0.46 | 0.64 | 0.26 | - | - | - |
| 45CrNi | 0.47 | 0.67 | 0.35 | 0.98 | 1.25 | - |
| 65Mn | 0.70 | 1.12 | 0.30 | - | - | - |
| T9 | 0.86 | 0.47 | 0.19 | - | - | - |
| T10 | 1.04 | 0.28 | 0.21 | - | - | - |
| T11 | 1.12 | 0.25 | 0.18 | - | - | - |
| 9CrSi | 0.91 | 0.43 | 1.35 | 1.15 | - | - |
| CrWMn | 1.03 | 1.04 | 0.27 | 1.13 | - | 1.48 |

Specimens of Φ (10-20) \times 5mm were quenched from temperature 860-1300°C, and holding time was 10-60 minutes. All the specimens possess Φ 3mm center hole. Steel 10, 20, 20Cr and 40 were quenched into cold salt water, and the other steels quenched into oil.

All the martensitic morphologies and substructures of these specimens were examined by using optical microscope, scanning electron microscope (SEM) and transmission electron microscope (TEM).

3. Experimental results and analysis

3.1. Three-dimensional morphology of low carbon martensite

The space morphology of martensite units in as-quenched low carbon steels was initially regarded as needles-like [1], and subsequently universally regarded as lath-like [2-8], such as "ruler" shape [4]. Fig. 1(a) is schematic diagram of the stereo shape of lath A and B which was plotted by Krauss et al [2], after 11 μ m and 18 μ m removed using electro-polishing, getting three polished surfaces of same place of a specimen, (see original Fig. 3). But it must be pointed out emphatically that any stereo models of martensite may be drawn on basis of these optical micrographs of three polished surface of specimen. Fig. 1(b) is a stereo pattern of thin sheet martensite plotted by the authors, and indicates that the image of the so-called "lath B" which was made up the three polished surface of specimen, may be constituted from the transversal sections of three thin sheets of martensite. That is, the stereo model of lath martensite proposed by Krauss et al is inappropriate and unreliable.

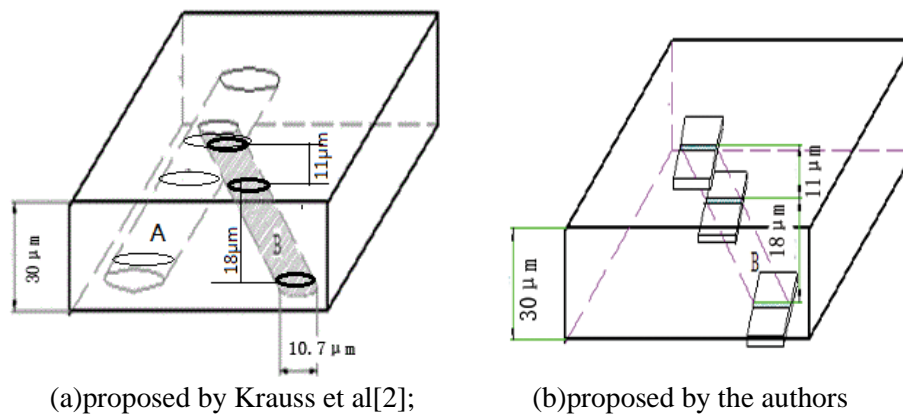


Figure 1. Schematic diagram of the stereo shape of laths martensite (a) and thin sheets martensite (b)

Fig. 2 is apparent morphologies of low carbon martensite under optical microscope (a) and SEM (b) and (c). The morphologies of as-quenched low carbon steels ($\leq 0.2\%C$) under optical microscope are consisted of alternating dark and light contrast packet martensite (Fig. 2 (a), its relative volume percentage is more than 30%) and single contrast packet martensite (the left in Fig. 2(a)). At higher magnification under SEM, these martensite packets appear to be composed of many mutually parallel fine platelets with thickness ranging $0.05\mu\text{m}$ to $1.5\mu\text{m}$, as shown in Fig. 2(b).

In order to ascertain the space morphology of these parallel fine platelets, thin foil specimens used in examination under TEM were observed again under SEM. It was seen that the two cross sections (perpendicular to each other) of a specimen all emerged many parallel platelets as thin sheet-like, and are not lath-shape, as illustrated in Fig. 2(c). Fig. 2(d) is an extremely difficultly found micrograph, showing a thin sheet shape. These micrographs irrefutably verify that the stereo morphology of low carbon martensite is not lath-like but rather thinsheet-like; therefore it was renamed to sheet-like martensite or packet thin sheet martensite by the authors [9-11]. Its three-dimensional model is shown in Fig. 3. Packet thin sheet martensite is formed by a number of martensite thin sheets stacking parallelly together along a same habit plane. There is an austenitic film between adjacent thin sheets [2-4] and the misorientation angle of neighboring thin sheets in a block is low angle difference [12, 13] and there is a twin boundary between adjacent blocks [2].

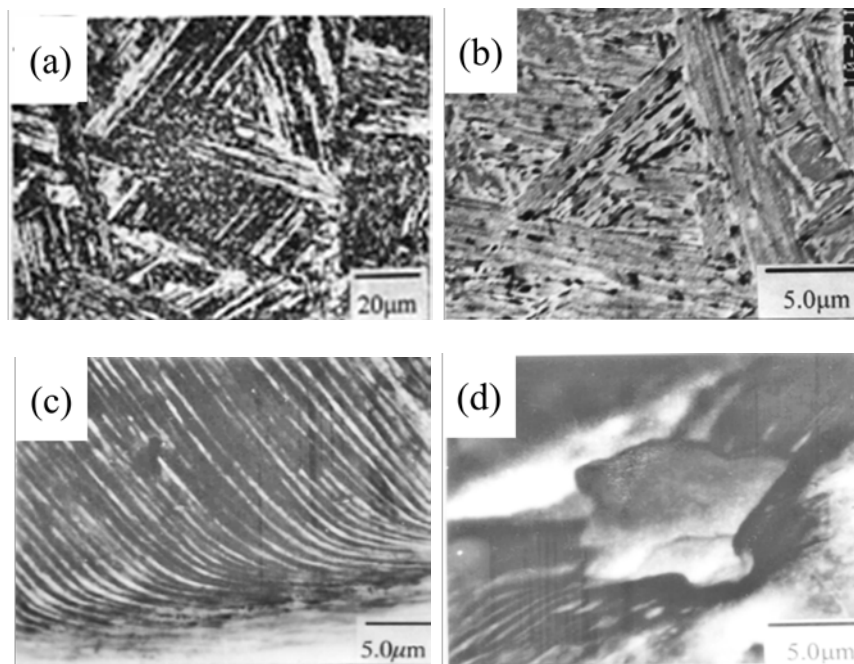


Figure 2. Optical micrographs ((a)) and SEMs ((b) ~ (d)) of steel 20Cr quenched from 1100°C ((a) and (b)) and steel 20 quenched from 1150°C ((c) and (d))

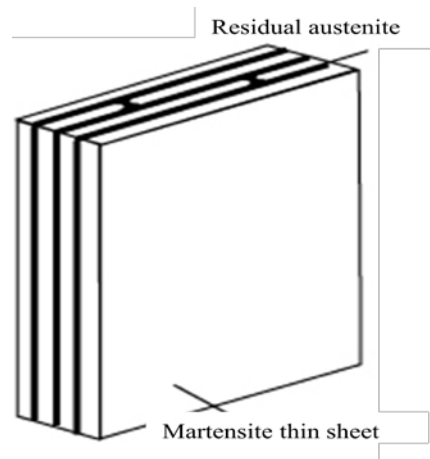


Figure 3. Model of low carbon martensite

3.2. Space morphology of medium and high carbon martensite

It was suggested firstly by Marder et al [12] that when carbon content was $<0.6\%$, $0.6-1.0\%$ and $>1.0\%$, the as-quenched microstructure was respectively lath martensite, mixture of lath and plate martensite, as well as plate martensite. Today, many researchers [4, 14] still hold on to this views, believing that all the packet martensite in medium and high carbon steels are lath martensite. [5-7, 14-16]

The as-quenched microstructures of five carbon steels ($0.4-1.1\%C$) and seven low alloy steels ($C < 0.4\%$) were observed under SEM and TEM [9-11, 17-21], and found that the packet martensite in medium and high carbon steels all was not lath martensite, but rather fine plate martensite. An example among them is shown in Fig. 4.

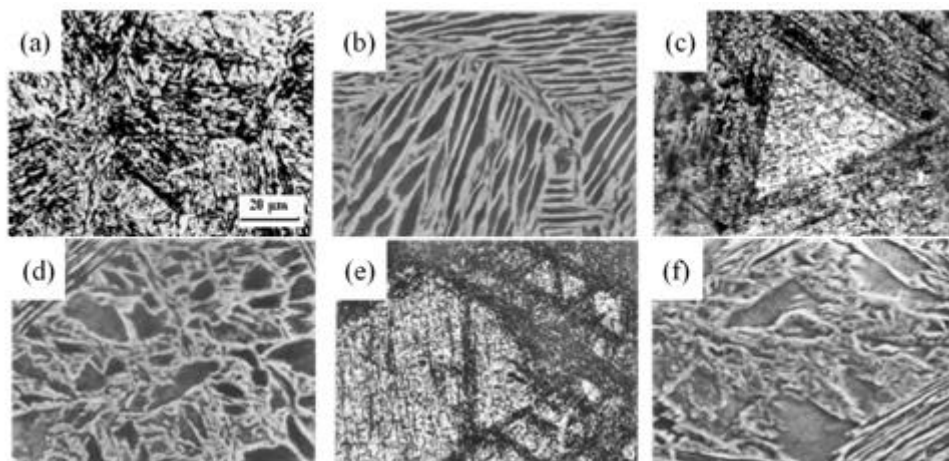


Figure 4. Optical micrographs ((a), (c) and (e)) and SEM ((b), (d) and (f)) of steel 40Cr quenched from $1100^{\circ}C$ ((a) and (b)), steel 40 quenched from $1150^{\circ}C$ ((c) and (d)) and steel 45 quenched from $1100^{\circ}C$ ((e) and (f))

It may be seen clearly from Fig. 4(a) that the overwhelming majority ($>90\%$) of packet martensite in medium and high carbon steel quenched from high temperature are single contrast packet and no block structure. At higher magnification under SEM, these packets appear to consist of many martensite narrow plates, big or small, parallel to one another, and the boundaries of fine martensite plates are unable to connect in a straight line (compared with Fig. 2(b)).

Sometimes a small amount of dark and light double contrast structures display too in local area of as-quenched microstructure of medium and high carbon steels, as illustrated in Fig. 4(c) and (e). In this instance, dark contrast packets always exhibit equilateral or isosceles triangular shape or an

included angle of 60° . At higher magnification, dark contrast packet is built up of many martensite parallel narrow plates (in the left upper corner of Fig. 4(d) and (e)) and light contrast region is composed of many martensite wide plates (in the centre of Fig. 4(d) and (f)).

Only when the observed plane of specimen is parallel to the habit plane of martensite, can the micrographs shown in Fig. 4(c) ~ (d) be obtained. On the grounds of a number of experimental observations, a stereo model of packet martensite in medium and high carbon steels has been proposed by the authors, as indicated in Fig. 5.

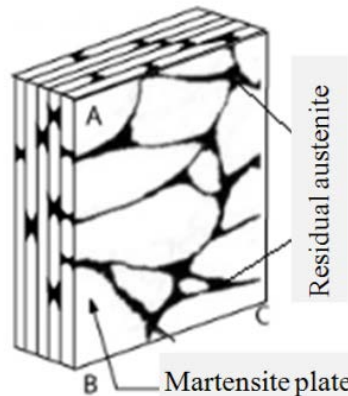


Figure 5. Model of medium and high carbon martensite

For lowering the barrier of nucleation and growth, the nucleation and growth of martensite plates proceed along the same habit plane, forming a group of packet plate martensite. All the neighboring martensite fine plates appear as curve line boundary and twinning relationship [22-24]. There is usually no residual austenite on the curve-line boundary [23, 25]. Residual austenite is mainly situated around each martensite plate.

The transverse section of the plate martensite packet will correspond to the dark packets in Fig. 4(c) and (e) and the regions of the narrow martensite plates in Fig. 4(d) and (f). If the longitudinal section of the plate martensite packet is parallel to the habit plane of martensite, the light region of Fig. 4(c) and (e) and the martensite wide plate region in Fig. 4(d) and (f) will appear. Therefore, the packet martensite in medium and high carbon steels has been named as fiber martensite [17, 18] or packet fine plate martensite by authors [9-11].

In summary, packet martensite in as-quenched steels should be divided into two categories: packet thin sheet martensite or sheet-like martensite, and packet fineplate martensite or fiber martensite. The former is universally displayed in as-quenched low carbon steels (the total alloy element content less than 5%), micro-carbon high alloy steel and so on, its nature is lath martensite; and the latter is generally exhibited in medium and high carbon steels quenched from high temperature, low carbon high alloy steels (the total alloying element content more than 5%), as well as higher carbon high alloy etc., its nature is plate martensite.

This is to say that the optical metallographical method identifying the type of martensite (its criterion identified is as-quenched microstructures presenting packets under optical microscope, are lath martensite), cannot correctly distinguish the kinds of martensite.

3.3. Habit plane of martensite

To date, the data of habit planes of martensite also are very different, the majority of researchers regard as to be $\{111\}$ [2, 26-28], or near $\{111\}$ [29], 4.5° from $\{111\}$ [30], $\{223\}$ [31], $\{213\}$ [32], $\{557\}$ [33-36] and $\{345\}$ [32].

During carbon content of 0.5-1.4%, habit plane of martensite in iron-base alloy is $\{225\}$ [37]; during 1.5-2.0% C, that is $\{259\}$ [38]. For Fe-5Ni-C, Fe-24Ni-2Mn, and Fe-20Ni-6Ti alloys, habit plane of martensite is $\{213\}$ [32].

In optical micrographs of Fig. 2(a) and Fig. 4(c and e), martensite packets all can compose an equilateral triangle, indicating that their observed surface of specimen all are parallel to (111) plane,

but the apparent morphologies of these two packet martensites are completely various. Dark contrast packets appear within an equilateral triangle of low carbon martensite (as indicated with the arrow in Fig. 2(a) and Fig. 6 (a and b)); at higher magnification (Fig.2 (b) and Fig. 6(c)), they were consisted of many parallel martensite thin sheets, which are parallel to a side of equilateral triangle. It is to say that (111) plane is not habit plane of low carbon martensite(for as-quenched steel 10 and 20Cr) and high carbon martensite(for as-quenched steel T10). However many martensite wide plates exhibit inside an equilateral triangle of mediumcarbon martensite (Fig. 4(d) and (f)), implying that this observed surface (111) is the habit plane of martensite mediumcarbon martensite.

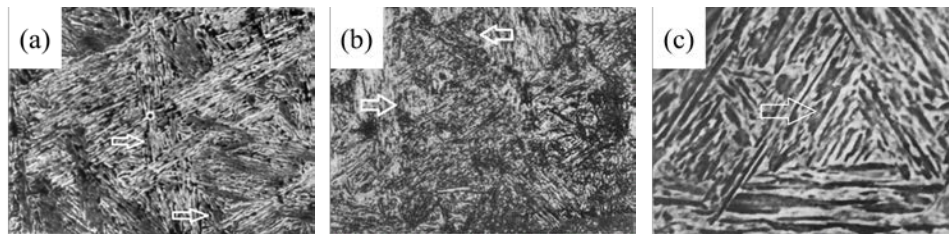


Figure 6. Optical micrographs ((b)) and scanning electron micrographs ((a) and (c)) of steel 10 quenched from 1200°C ((a)) and steel T10 quenched from 1100°C ((b) and (c))

Geometric analysis of two habit planes is shown in Fig. 7. The intersecting lines BC, AC, and AB of habit planes $(\bar{7}55)_r$, $(5\bar{7}5)_r$ and $(55\bar{7})_r$ with plane (111), respectively (Fig. 7(a)), may compose of an equilateral triangle but wider sheets cannot be seen on plane (111), inasmuch as it is not habit plane of low carbon martensite, see Fig.2 (b) and Fig. 6(c). Similarly, the intersecting lines BC, AC and AB of habit plane $(1\bar{1}1)_r$, $(\bar{1}11)_r$ and $(11\bar{1})_r$ with plane (111), respectively (Fig. 7(b)), not only may make of an equilateral triangle but also martensite wider plates can be observed on the plane (111) see Fig. 4(d) and (f), it is therefore habit plane.

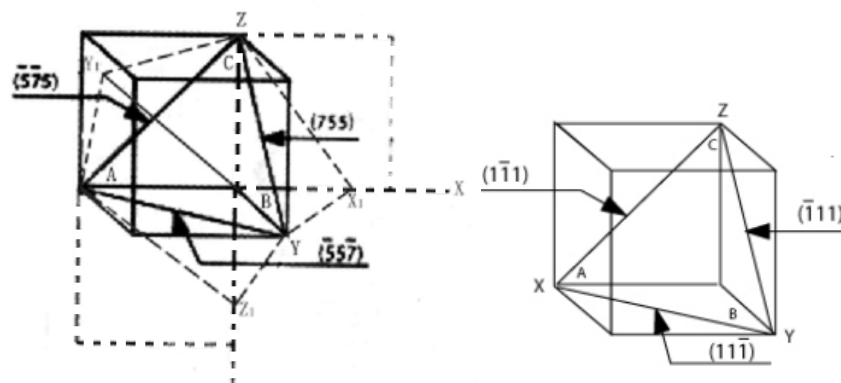


Figure 7. Geometric patterns of habit plane $\{557\}_r$ (a) and $\{111\}_r$ (b)

That is, the habit plane of low carbon martensite is $\{557\}_r$ or $\{223\}_r$, rather than $\{111\}_r$, $\{213\}_r$, $\{345\}_r$ etc. Since for the former, there are no martensite wide sheets inside equilateral triangle to emerge; for the latter, these three habit planes, of which three crystal face indices are all different, cannot comprise equilateral triangle.

In addition, many researchers [33-36] have obtained that the habit plane of low carbon martensite all is $\{557\}_r$, there is only a report [31] proposing that the habit plane of low carbon martensite is $\{223\}_r$, therefore, $\{557\}_r$ should be the habit plane of low carbon martensite.

It can be known from Fig. 4 that the habit of martensite mediumcarbon martensite is not $\{225\}_r$, but rather $\{111\}_r$. The identical results with Fig. 4 may also be observed in as-quenched steels containing 0.4~0.9%C [45].

Single contrast packets may build up of equilateral triangle for T10 steel quenched from 1100°C (Fig. 6(b)), but no light contrast image appears within equilateral triangle (unlike Fig. 4(c)); at higher magnification (Fig. 6(c)), there are only many parallel martensite fine narrow plates and no martensite wide plates. The habit plane of martensite in T10 steel thereby is $\{225\}_r$, but not $\{111\}_r$. Same results as T10 Steel were also yielded in as-quenched steels containing 1.0-1.4% C.

In sum, it have been drawn on the basis of a number of experimental observations by the anthers, and other available experimental data that when the total amount of alloying element is less than 5%, martensite habit plane is directly related to the carbon content. During $C \leq 0.3\%$, the habit plane is $\{557\}_r$; during $C = 0.4-0.9\%$, that is $\{111\}_r$; during $C = 1.0-1.4\%$, that is $\{225\}_r$; during $C > 1.5\%$, that is $\{259\}_r$.

In terms of the habit plane and morphology of martensite unit, it has proven that packet martensite can be divided into two categories four kinds. Two categories are: packet thin sheet martensite (recisely speaking to be $\{557\}_A$ packet thin sheet martensite, i.e. “lath martensite”) and packet fine martensite (belong to “plate martensite”), Packet fine plate martensite again may be divided into three types: (1) $\{557\}_A$ packet fine plate martensite, forming in the low carbon high alloy steel; (2) $\{111\}_A$ packet fine plate martensite, appearing in medium carbon hardened steel; (3) $\{225\}_A$ packet fine plate martensite, occurring high carbon quenched steel. Coupled with $\{557\}_A$ packet thin sheet martensite, total is four kinds packet martensites.

3.4. Substructure of martensite

Until now the reports concerning the observation of internal twins in lath martensite may be divided into two types. First, there are no [39] or rarely [40] internal twins within lath martensite; second, lath martensite within numerous internal twins were found in many alloys [41-43]. This discrepancy is also related with not differentiating the type of packet martensite. Because the as-quenched microstructures of 0.2%C-3.SCr-5Ni steel[42] (see original Fig. 5(C) and (D)), AISI 4340 steel[43] (original Fig. 4 and 7), 0.24C-9Ni-7Co alloy[41] (original Fig. 3) in which numerous internal twins were seen, all are a single contrast packet martensite and the total amount of alloying element is more than 5%, thus they should be plate martensite instead of lath martensite. That is to say that martensite of which substructure is numerous internal twins, all is plate martensite and not lath martensite.

Martensite in different carbon content steels all possess internal twins; with an increase in carbon content, the amount of martensite units with internal twins enhances and distance between internal twins diminishes. There is hence no noticeable variance between the substructures of lath and plate martensite under TEM, that is, TEM identifying the type of martensite also cannot correctly distinguish lath martensite and plate martensite.

4. Conclusions

Packet martensite can be divided into two categories and four kinds. Two categories are: packet thin sheet martensite ($\{557\}_A$ packet thin sheet martensite, i.e. “lath martensite”) and packet fine martensite (belong to “plate martensite”), the former forming in low carbon steel and low alloy steel, the latter emerging as in medium and high carbon steel, high alloy steel. Packet fine plate martensite can be divided into three types: (1) $\{557\}_A$ packet fine plate martensite (low carbon high alloy steel); (2) $\{111\}_A$ packet fine plate martensite (medium carbon hardened steel); (3) $\{225\}_A$ packet fine plate martensite (high carbon quenched steel). Space morphology of low carbon packet martensite units is sheet-like but not lath-like; that of martensite medium and high carbon packet martensite units is plate-like.

During $C \leq 0.3\%$, the habit plane of martensite is $\{557\}_r$; during $C = 0.4-0.9\%$, that is $\{111\}_r$; during $C = 1.0-1.4\%$, that is $\{225\}_r$; during $C > \text{about } 1.5\%$, that is $\{259\}_r$.

There is no noticeable difference between the substructures of lath and plate martensite. Martensite without internal twin is not certainly lath martensite, while all martensite with numerous internal twins is certainly plate martensite.

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