"Complete Twin" and "the Transgranular Twin Line" of Common Steels

Long Wang[1], Guofei Cheng[1*], Ting Liu[1], Junbao Yang[1], Ligang Ding[1*], Yuexin Ma[1] and Yuhua Tan[2]

[1]Zhongshan Torch Polytechnic, Zhongshan, China
[2]Xiangtan University, Xiangtan, China
[*]Email: kingkingv@126.com, 460050877@qq.com

Abstract. Themicrostructures of 20, 30, 40, 45, T9 and T11 commercial carbon steels were observed by optical microscopy, scanning electron microscopy and transmission election microscopy. It was found that the internal twins in martensite of common steels is basically a complete twin, and internal twin plane of mutually parallel martensite units in a martensite packet have a same crystallographic orientation, namely, forming "the transgranular twin line" or "interpenetration twinline". The underlying mechanism of "complete twin" and" the transgranular twin line" were explored. Both all are to form in the martensite transformation process. In order to promote the growth of martensitic nuclei in initial stage, the associated nucleus with twinning relationship had been formedat a semi-coherent end plane of nuclei which possesses high energy, and forming transformation twins through "double change". Therefore, transformation twins are usually all "complete twin". In the martensite packet, all the martensite plates of mutual parallelism are to form the associated nucleus with twin interface plane at a side of original " twin block" of the martensite and grow up, so a martensite packet all have the identical "trans-granular twin line". In the formation process of "complete twinning" and" trans-granular twin line", don't involve the mechanics properties of material, and mainly decide from nucleation work and nucleus growth work. It is thus clear that, having the complete twins in the martensite doesn't mean that the critical resolved shear stress (CRSS) of slipping exceeded the CRSS of twinning.

1. Introduction

The twinning in martensite has two morphologies: complete twin and partial twin. The current complete twins all were to observe in the lenticular martensite and coarseplate martensite of Fe-Ni and Fe-Cr high alloys [1~6]. In lenticular martensite, we also have seen partial twin [7, 8].Generally considered, martensite in ordinary steel all is "partial twin martensite". Most are of twinning {1 1 2} M, sometimes are twinning {0 1 1} M [13]. Usually the {1 1 2} M twin was thought to be transformation twins, while the {0 1 1} M was a deformation twinning when collaborative deformation. Up to now believe that "transformation twins are through the plastic deformation of martensite to generate [14]."Sub-structure" within the martensite is a product of local (heterogeneous) twin shear during phase transition [15]. In the process of martensite transformation, plastic deformation of high carbon martensite is by means of twinning to carry out [14]. The twins generated were called "transformation twins" [6, 7].That is to say, “twins” is not in accordance with the produced causes of twins, but to be defined according to "the twin to form in what process”. In their eyes, there is no difference between "transformation twins" and "deformation twinning" in essence, or to say, "internal twins" all are generated by the "twinning shear", the difference is only "the transformation twins are to appear in the process of phase transition".

In this paper, the results of the experiment have confirmed that in martensite of carbon steel internal twins all are complete twin.

2. Materials and procedures

Using six kinds of commercial steel: 20(0.19%C), 30(0.27%C), 40(0.38%C), 45(0.46%C), T9 (0.86%C), T11 (1.12%C), etc. Machined into sizeΦ10 x 5 mm, all test specimens possess a central hole with diameter of 3mm. All samples were heated in controlled atmosphere furnace, quenching water from 1000 ~ 1350 ℃.

After samples have been prepared, their microstructures were observed using a Polyvar MET optical microscope, scanning electron microscope S-570 and Philip ECNAI-G2 transmission electron microscope.

The specimens of transmission electron microscopy were etched with saturate alcohol of picric acid containing 1.3% HNO3, 2.1%HCl and 2.7%CuCl2. Operating temperature was around -10 ℃.

3. Experimental results and analysis

3.1. Morphology of internal twins in common steel

Fig. 1 shows the images of whole packet martensite of low carbon steel 20 and medium steel 40 quenched from high temperature. The morphology of these two kinds of packet martensite is entirely different. Under optical microscope, 20 steel is a packet structure which is composed of dark and light double contrast blocks, as shown in Fig. 1 (A); while the 40 steel is all a single contrast packet structure, as illustrated in Fig. 1 (D).Under the SEM, the smallest unit of martensite in 20 steel appears a parallel thinplate-shape with similar thickness and straight line interface, such as in Fig.1 (B);while the 40 steel is made up the parallel fineplate with different size and curved interface, shown in Fig.1(E).Under the TEM, the most substructure of 20 steel are dislocation tangles; By means of rotating the thin foil specimen 7.2 degrees, in some block was observed internal twins, average spacing of twins plane is about 0.227 μ m, see Fig. 1 (C). After 40 steel rotates 9°, it also shows a lot of internal twins, the average distance is of about 0.128 μ m, see Fig. 1 (F); twin density increases dramatically.

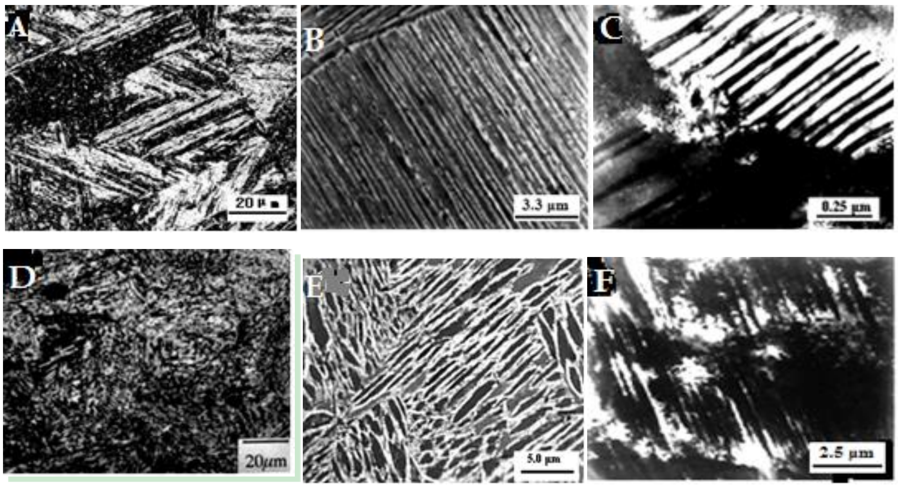

Figure 1. Optical micrographs (A, D) and SEM ((B, E) and TEM (C, F)) of steel 20 (A~C) and T11 (D~F) quenched from 1100 ℃

Worthy of special attention are: Fig.1 (C) is "complete twin" to across the whole martensite single crystal, and the orientation of twinning plane is the same with the around single crystal. Twinning in Fig.1 (F) also is to across the martensite plate, since only local corrosion is too thin, it was punctured by the electron beam, don't appear the diffraction contrast image of twinning, it thus was often mistaken for "partial twins".

The observations of Fig.2 confirmed once again the universality of the above conclusion. The internal twins of 30 steel (Fig. 2 A) not only traverses the parallel thinplate crystal, and the twin plane of 6 thinplate crystals in a field view is a same orientation. The orientation of internal twin plane in a same block all is identical. A martensite plate (sheet A) in Fig. 2 (B) possesses a midrib line, the dense internal twins traversed through the whole martensite plate. In addition its twin plane with a above martensite plate (sheet B) have the same orientation.

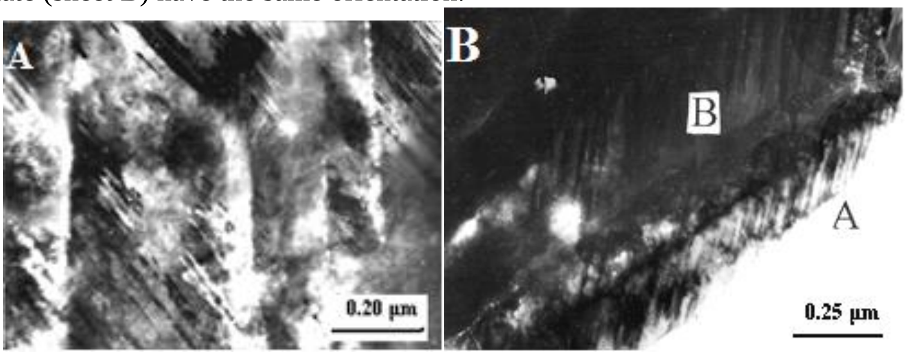

Figure 2. TEM of 30 and T11 steels quenched from 1100 ℃ (A): rotating 6.8 °; (B) rotating 3.5 °

Usually, above a martensite plate (Fig. 2(B)) was often regard as a partial twin, this is a misunderstanding. At this time, the diffraction contrast image of internal twins is the above being wide, the below narrow, presenting a tapering angle shape. This appearance is caused by a thin foil specimen preparation process. Here is make by a double corrosion into the non-uniform thickness, as shown in Fig. 3 (A), the local of thin foil specimens becomes a triangle podetium. After twotriangle twinning planes produced diffraction, the intensity of the incident electron beam was weaken, the image of △ a1b1c1 (light colored triangles) and △ a2b2c2 (hatching triangle) displayed. Diffraction contrast image of triangle twinning plane overlaps in the thicker of thin foil sample, exhibiting the black color. Only in the thiner of thin foil sample, the diffraction contrast image of internal twins does not overlap, to show the image with tapering angle shape, as presented in the graph (a) of Fig. 3 (B).

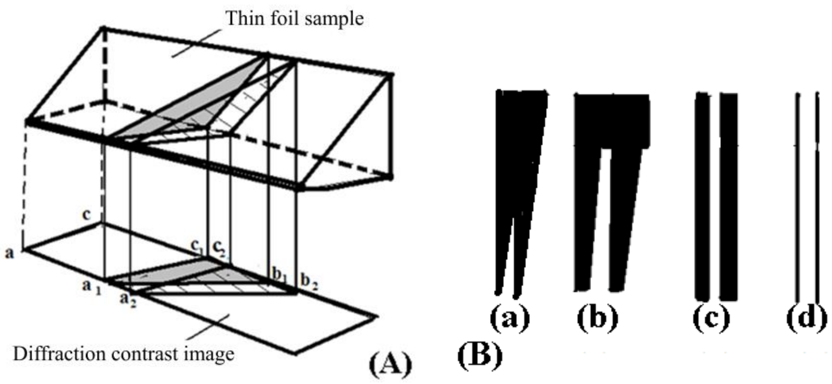

Figure 3. Schematic illustration of formed image of internal twins

Along with the thick end of sample thinning, and the thin end thickening, diffraction contrast image will show a rectangle, as shown in graph (b) of Fig. 3 (B); the overlap region of diffraction contrast image also becomes small. This is the reason of martensite B in Fig. 2 showing a black strip shape. The both ends of the internal twins in Fig. 1 (F) is not complete, showing sharp, also is such to form. If the sample thickness is uniform everywhere, so the diffraction contrast image of twinning plane will become as shown in Fig. 3 (c), presenting the parallel narrow strip. The internal twins in Fig. 1 (C) are such to form. Just because the sample surface is not flat, so that the diffraction contrast image edge of internal twins is not smooth. When the sample is very thin, internal twinning plane will become into a thin strip. After it produces diffraction, if the intensity of incident electron beam is very weak, internal twinning will emerge as many parallel lines (see Fig. 3 (d)). The most diffraction contrast images of twinning plane in martensite plate A in Fig. 2 (B) are straight line, it is because this place of sample is thinner and uniform.

It should be pointed out; we also observed some TEM images in which internal twins are located in centre of martensite plate, such as in Fig. 4B. They are not a "partial twin "which was considered by literature [9]; this phenomenon is entirely caused by local deep corrosion of thin foil specimens.

Because of the different orientation of martensite on both sides of the grain boundary, the vicinity of the boundary area was etched too much, very thin, while the central is thick; the diffraction contrast image of thin twin plane does not show (white color) or too thick, diffraction contrast image overlap, also not see (black color), resulting a result of Fig.4B.

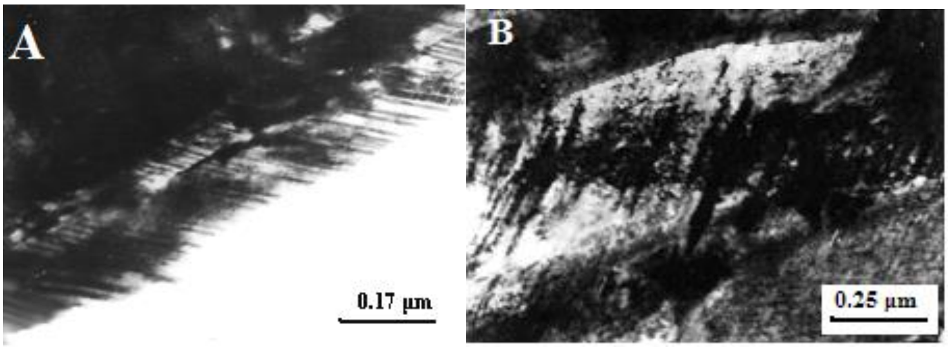

Figure 4. TEM of T9 steel quenched from 1000 ℃ (not tilted), 40Cr steel quenched from 1150 ℃ (1.5 °tilted)

In Fig.4A, whole martensite is all complete twinning within the two plates of parallel martensite. Not only the whole of internal twin lines is parallel, moreover, some are connected together in a straight line.Illustrated fully that they are closely connected within the process of their formation. Entire twin planes possessed the same orientation in a packet martensite, were called "transgranular twin line" or "interpenetration twin".

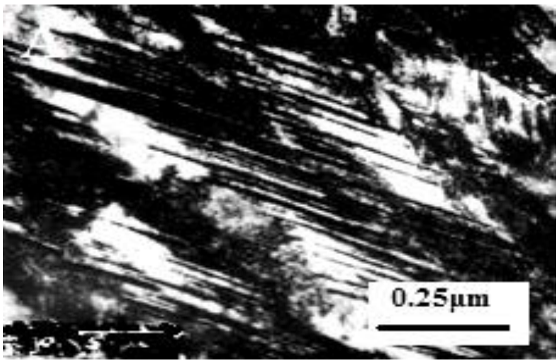

Figure 5. TEM of 0.7%C steel [18]

We confirmed two new views: (1) internal twins generated in the process of martensite transformation (i.e., the transformation twins) is basically complete twin; (2) in a martensite packet, martensite units parallel to each other have a same orientation of twinning plane, that is "transgranular twin crystal line". The same observation was also seen unexpectedly by Carr M J. et al [18], fully validating our results, but they had not specifically mentioned, either explored the reasons for their formation or interpreted their role on martensite transformation.

3.2. Complete twins and transgranular twin wire forming reasons

At present, the interpretation of the above two phenomena has not yet provided. In another paper [22], we demonstrate in detail the forming mechanism of internal twins in the martensite transformation process. Pointing out that "the transformation twins" is not generated by martensite plasticity shear, but rather a product of the growth process of martensite nucleus. This paper proposes a new mechanism of twin formation: Relying on the unceasingly changing the growth direction of crystal nucleus, making a new produced crystal to have a orientation difference of "twin angle", thereby forming a "twin".

The procedure which can significantly change the "orientation" and do not cause the interface to increase, is "double-change" proposed by the data [20].Namely when the crystal nucleus grown, because austenitic direction $\langle 1\ 1\ \bar{2}\rangle$A changes 60 °, and simultaneously alters austenitic direction $\langle 1\ 1\ 0\rangle$ A parallel to martensite nucleus, also yielded orientation difference 10 °32 ′(i.e. 60 °+10 °32 ′=70 °32 ′) , thus appeared the misorientation of twinned angle (70 °32 ′), making the formation of twin interface between two adjacent martensite crystals. It can be seen from here that internal twins in martensite is completely to form spontaneously in the process of transformation, in order to favor the growth of martensite nucleus. It is an important way of nucleus growth in the early period of martensite nucleation.

"Transgranular twin line" is also on the aforementioned basis to produce. The following will show the formation mechanism of "complete twin" and "transgranular twin line" combined with Fig. 6 and 7.

Because the martensite nucleus size is small, the consumption proportion of interfacial energy in the driving force of phase transition is high; the initially formed nucleus is thin film-like, as shown a dark blockinplate A in Fig. 6.Only a few atomic layers thick, two main interfaces are parallel to the habit plane in order to maintain the minimum interface energy; it hence has thin-plate-like in shape.

In this moment, the volume free energy only can drop a little, not can thickening; because the thickening leads the semi-coherent interface area of nucleus around to increase. This nucleus grows towards two other directions, to expand the main interface parallel the habit plane. When the volume strain energy and interface energy equals to the driving force, the growth of nucleus a stops, becoming a dark square crystal block a in Fig. 6.It is only by way of the "double change" (namely "changing" grew up direction, and by the $[1\ 1\ \bar{2}]$A into $[2\ \bar{1}\bar{1}]$A, and "changing" parallel to the direction of the austenite), to continue to grow up, forming a crystal block b with “twin interface" on the end face of the dark square crystal block a; because of "twin interface" reduced "interfacial energy", and prompted dark tetragonal block a to obtain transverse grewth conditions, thus becoming into a twin long block (light color in Fig. 6). When the crystal block b stops growth, adopts to form a crystal block c with twin interface in the bottom of crystal block b, prompting crystal nucleus b also to grow a light twin long block(see Fig. 6) . So repeatedly, then it forms a thin film crystal block with many twin interfaces, and becomes a film crystal, such as a colored film crystal within martensite plate A. Insomuch as "internal twins" in martensite plate A is relying on the growth direction of crystal nucleus to alter the 70 °32 ′ (i.e. "twin angle) to produce, therefore they all grew into "complete twin".

On account that the volume of light colored film crystal increases largely, the volume free energy decreased much; simultaneously since the volume strain energy increases, making the proportion of interfacial energy in nucleus growth work to become small, it creates conditions for the nucleus thickening; finally growing into a martensite plate with lots of internal twins, as shown the plate A in Fig. 6. It can be seen from here that plate A is through thickening of "colored film crystal" to generate.

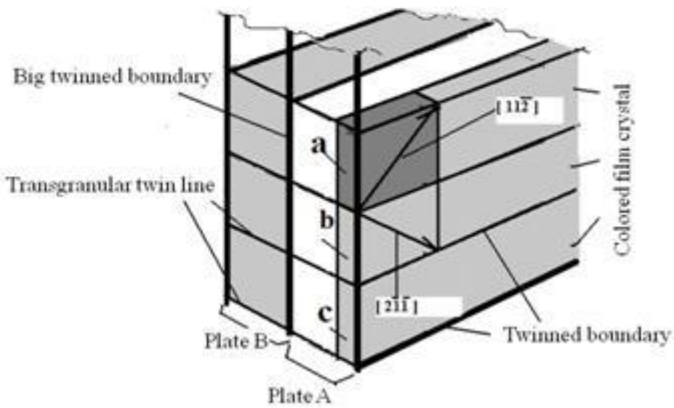

Figure 6. The nucleus growth of packet fine plate martensite

After the plate A stopped growth, through the "double change"[22] to generate a associated nuclei with twin interface beside each internal twins, it develops into a plate B which keeps a twin interface with plate A. By reason that twin block inplate B all is by way of the formation of associated nucleus with twin interface beside the twin block inplate A to produce, hereby all the orientation of twinning plane inplate A are preserved. This leads to the orientation of each twinning plane of neighboring martensite plate to be same, becomes a communal twin interface line as shown the straight line in Fig. 5 ~ 7. This "transgranular twin line" traverses two martensite plates. Now the interface between A and B plate was called "big twinning plane".

Four twin blocks (i.e. internal twins) on the left of Fig. 7 (A) is located in the "martensite plate A" which has been formed, their internal twin planes are a, b, c, d. The formation of "martensite plate A" is to rely on changing the growth direction of internal twins (such as “arrow”).

Associated nucleus (h g K H L B light colored crystal B in the picture) which formed on the side of "martensite plate A" is also twinning relationship with martensite plate A, but its twinning plane becomes into E F C G H D E (referred to as the "big twinned boundary" in the picture), their mirror symmetry relations are as shown the crude dotted arrows in Fig. 7. As a result of that these associated crystal nuclei is to grow up on the side of each twin block of the originalplate A, thus keeping the original twinning interface (or twin line). After they grow up and become two adjacent martensite plates of A and B, this twin line shared, as illustrated in Fig. 7 (B). In this picture, there are three martensite plates A, B and C which are parallel to each other and have the twin relationship (that is with “large twin boundary”); their internal twin planes (the diagonal in the picture) possess the same orientation, namely retaining the same "transgranular twin line". "Transgranular twin line" and the habit plane are skew.

In so much that the adjacent twin blocks all keep the twin interface in originalplate A, this is a reason why various martensitic fine plates parallel to each other in a cluster have the same "transgranular twin line", as presented in Fig. 1 (C) and (F), Fig. 2, Fig. 5 and Fig. 6.

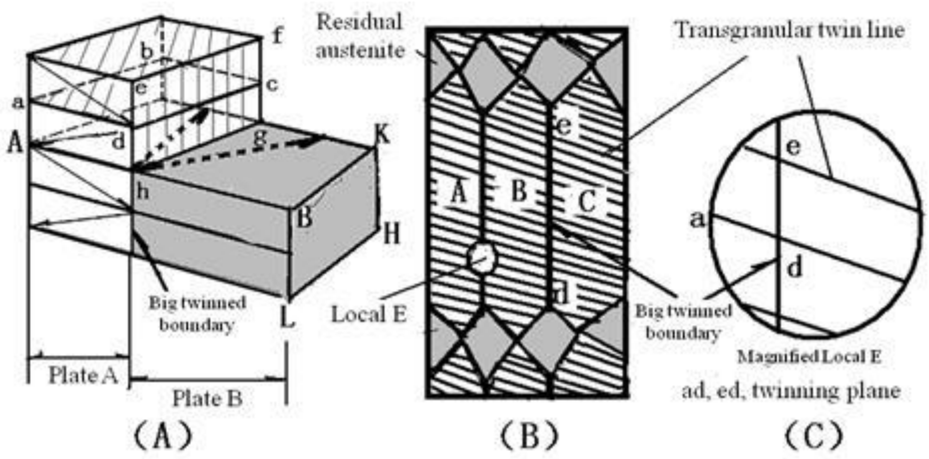

Figure 7. Schematic resolved illustration of formation process of packet fine-plate martensite

In the transformation mechanism of fine plate martensite [20], the twinning relationship between associated nucleus B and the original nucleus A is the most important, otherwise the adjacent martensite plates (such as the associated martensite plate A and B in Fig. 7 (B)) cannot produce, phase transition will not be able to continue.

Fig. 7 (C) is a enlarged diagram of circle "local E" in Fig. (B), marks the two kinds of twinning plane: internal twin plane is a-d (i.e. transgranular twin line) and the large twin plane between martensite plates A, B, C is e-d.

As can be seen from above, when formed "complete twin" and "transgranular twin line" in the martensite transformation process, it does not related to the mechanical properties of the material, mainly decided by nucleation and nucleus growth work. These twins all are "transformation twins". From beginning to end, did not occur the heterogeneous plastic shear of martensite in the process of phase transition, and generate the twinning by means of martensite's plastic deformation. It can be seen from here that martensite possessing complete internal twins does not mean that the critical resolved shear stress of slipping exceeds that of twinning. From the above discussion, it can see clearly that "martensite shear theory" does not conform to the actual martensite transformation, that the plate-like shape of martensite and internal twins were regarded as a cause of martensite high brittleness is purely the prejudice of "martensite shear said".

4. Conclusions

All martensite have internal twins, they are formed in the initial stage of the martensite nucleation, and belong to transformation twins. With increasing the content of carbon and alloy elements, internal twinsdensity enhances. When containing 0.19%C, 0.38%C, 0.86%C, 1.12%C, the average distance of internal twins were 0.227, 0.128, 0.034 and 0.011 μ m respectively.

"Transformation twins" in common steel is usually "complete twin". Every martensite unit in packet martensite has a same orientation of twinning plane, namely forming "transgranular twin line". Complete twin and transgranular twin line all are to generate in the martensite transformation process in order to reduce the nucleation and nucleus growth work, have nothing to do with heterogeneous plastic shear of martensite.

When the thin foil specimen was carried by twin-jet erosion, due to uneven corrosion, it often changes the morphology of diffraction contrast image under TEM, and leads to one's beyond recognition, and complete twin often turns into partial twin.

5. Reference

[1] D F Li, X M Zhang, E Gautier, J S Zhang 1998 Acta Met. 46 13 4827-4834
[2] S B Seo, J H Jun, Ch S Chong 2000 Scripta Mater. 42 123-127
[3] Sh K Zheng, Zh Zh Mu 1974 Journal of Japan metal 13 5 329-339

[4] H Okamoto, M Oka, I Tamura 1976 Proc. of First J I M, Intern. Symp. On New Asoects of Martensite Transformation, Kobe, 47-58
[5] I Tamura 1976 Proc. of First J I M, Intern. Symp. On New Asoects of Martensite Transformation 59-68
[6] D F Li, X M Zhang, E Gautier, J S Zhang 1998 Acta Met. 46 13 4827-4834
[7] Y.H. Tan, D.C. Zeng 1992 Natural Science J. of Xiangtan University (China) 14 93
[8] A Shibata, H Yonezawa, K Yabuuchi 2006 Materials Science and Engineering. A 438–440 241–245
[9] Q Chen, X F Wu, K E Jun. 1997 Science in China A 40 632
[10] G Krauss, A R Marder 1971 Metall. Trans. 2A 2343-2357
[11] G R Speich 1972 Metall. Trans. 3A 1043
[12] H Okamoto, M Oka, I Tamura 1976 Proc. of First J I M, Intern. Symp. On New Asoects of Martensite Transformation, Kobe, 47-58
[13] J A Klostermann, W G Buegers 1964 Acta Met.12 355
[14] M X Zhang, P M Kelly 2001 Scripta Mater. 44 2575-2581
[15] Z Y Xu 1999 Science press.
[16] K M Knowles 1982 Phil. Mag. 45A 357
[17] Sh Z Chi 1981 Iron and Steel. 67 7 852-866
[18] M J Carr 1978 Metall. Trans. 9A 857-864
[19] D Srivastava, P Mukhopadhyay, S Banerjee 2000 Mater. Sci. Eng. A 288 101-110
[20] Y J Liu, B Y Huang, Y H Tan 2005 Transactions of Materials and Heat Treatment. 26 1 48-52.
[21] Y X Ma, Y H Tan 2011 Proc. of Heat Treatment (CMES) Tianjin. 209-215
[22] Y X Ma, Y Wu, D C Zeng, Y J Liu, Y H Tan 2013 Heat Treatment of Metals. 38 7 46-52