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THEORY OF METALS

Key Role of Transformation Twins in Comparison of Results of Crystal Geometric and Dynamic Analysis for Thin-Plate Martensite

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Abstract—The experimental data on the ratio of transformation twins fractions for crystals of thin-plate α-martensite (with the habit planes of the $\{2\ 5\ 9\}_\gamma$–$\{3\ 10\ 15\}_\gamma$ type) are considered. It is shown that the dynamic theory of the martensite crystals formation is free from the difficulties encountered in the formal crystal geometric approach. The intervals of parameter values that correspond to the observed fractions of the twin component, δ_{tw}, within the same crystal are given. The absence of twinning in thin plate-like crystals, which sometimes are observed in experiments on the γ–α martensite transformation induced by strong magnetic field is discussed.

Keywords: martensitic transformation, thin plate-like crystals, transformation twins, dynamic theory, fraction of twin component

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INTRODUCTION

The crystal geometric approach to describing the macroscopic morphological features of martensite crystals (habit plane, macroshift, orientation relationships (OR)) was proposed in [1]. The fundamental postulate of the approach declares the habit plane to be the macroscopically invariant one. The most impressive success of this approach was the prediction of the need for crystal twinning and the calculation of the fraction ratio β_{tw} of transformation twins in crystals with habits $\{3\ 10\ 15\}_\gamma$, which were observed for the first time in [2] in the alloy Fe–22Ni–0.8C during γ–α martensite transformation (MT). It must be emphasized that, according to [1], a particular habit plane is associated with a well-defined (fixed) value of β_{tw}. However, it was shown in experiments [3] that the β_{tw} value varies not only during the transition from crystal to crystal, but also within the same crystal. Actually, this fact is well known by metal physicists and clearly seen in the images of the observed twinned structures of thin plate-like crystals, examples of which taken from [3] and [4] are shown in Figs. 1 and 2.

Figures 1 and 2 show that, although there is a tendency toward regularity, the twin structure is not strictly regular, but this fact does not exclude its existence as an ideal limiting case.

It should be noted that the authors of [3] did not restrict themselves to the fact that β_{tw} varies but also undertook measurements, which evinced that the volume fraction of twin component δ_{tw} showed variation between $0.37 < \delta_{tw} < 0.46$. Since the expected value of δ_{tw} based on [1] corresponds to the central region of the observed range, the satisfactory agreement between

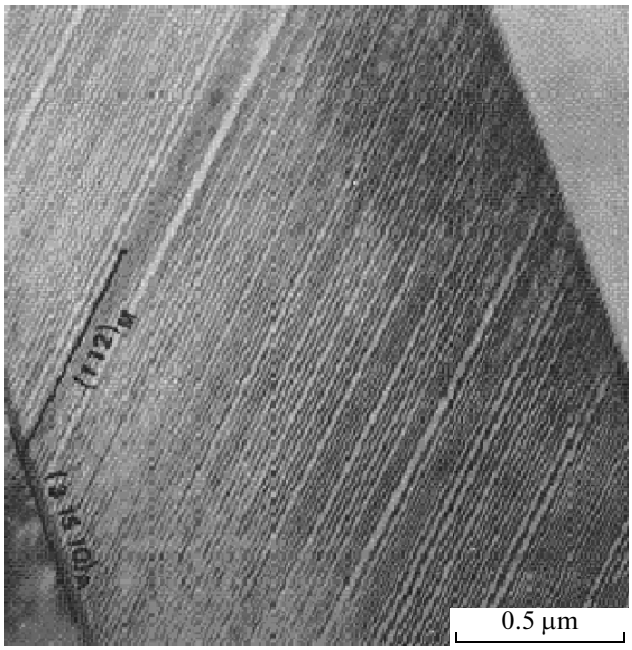

Fig. 1. Common structure [3] of martensite crystals in the alloy Fe–30Ni–0.39C: twinned thin plate-like crystal.

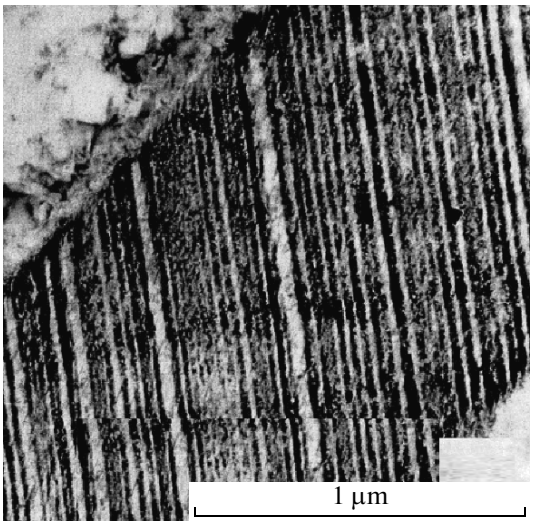

Fig. 2. Common structure [4] of martensite crystals in steel 52H2N23: twinned thin plate-like crystal.

observed and expected results was concluded in [3]. However, the authors of [3] had no other choice because no alternative explanations existed. It is worth mentioning that crystal geometric approach from the very beginning was only intended to solve problems dealing with the consistent description of morphological properties and did not claim to be a physical MT theory capable of describing all of the characteristic properties of a martensite reaction. However, within the specified limits, the crystal geometric approach has well-known problems concerning the determination of the morphology of crystals with the $\{225\}_\gamma$ habit planes (as well as the $\{557\}_\gamma$ habit planes of packet martensite), although its applicability to the morphology description of the thin plate-like martensite crystals with $\{3\ 10\ 15\}_\gamma$ habit plane was considered to be the reference, despite the variations in δ_{tw} marked in [3].

The purpose of this study is to show that the dynamical MT theory developed within the new paradigm [5–10] makes it possible to naturally explain the observed features of the twinned crystals formation, including the absence of twinning observed, albeit rarely, in the experiments in [4] dedicated to the induction of MT in strong pulsed magnetic fields.

1. DYNAMIC THEORY OF THE FORMATION OF TWINNED MARTENSITE CRYSTALS

For the readers convenience we recall, in a qualitative way, part of the dynamic approach [5–10] ideology, which is based on the supersonic martensitic crystal growth model. A crystal forms during the propagation of the control wave process (CWP) that carries a threshold deformation that destroys the prior austenite stability in the lamellar region. Thus, the orientation of the crystal habit is defined directly by the CWP in the threshold mode, while the orientation relationships and macroshift occur after the region of the crystal lattice where it has lost stability acquires the deformations exceeding the threshold one by two to three orders of magnitude. This picture is directly related to the representation of an initial excitation (vibronic) state, which lies at the heart of a new paradigm for the transformations that occur in the supersonic regime. Note that the traditional paradigm of first-order phase transitions in solids (which is based on the idea of the existence of a quasi-equilibrium nucleus of the new phase) as regions with different lattice symmetry and isolated by the system of defects (usually of dislocation origin) retains its significance for transformations that take place at subsonic speeds.

According to the developed dynamic theory, the twinning process is considered as a consequence of the consistent propagation (and actions) of relatively short-wavelength displacements (s waves) that travel along orthogonal axes of fourth-order symmetry, and relatively long-wavelength displacements (ℓ waves) that define the crystal habit. The superposition of s waves initiates the formation of a twinned structure (TS) main component at supersonic speed. The mode of the consistent start and propagation of s- and ℓ waves, followed by the periodic reproduction of an active $s-\ell$ cell in the central area of the CWP front, is responsible for the case when a perfect regular TS forms. This cell has the shape of an elongated rectangular parallelepiped with equal short ribs. The formation of the twin components is subordinate. Its origin is dictated by a pair of fringing main components that preserve coherent coupling with an interlayer separating them. The thickness of a thin plate-like crystal is about half of the length of ℓ waves and the twin main component thickness is of the order of the half length of the s waves.

Figure 3 shows a section of a three-dimensional pattern of periodic layered structure formation in the threshold mode. It is clear that the formation of twinned crystal is a special case of such a structure.

The image plane coincides with $(001)_\gamma$ one that located at the angle ψ to the axis $[100]_\gamma$. Normals of s-wave pair and the projection $\mathbf{n}'_{2\ell}$ of the wave normal vector $\mathbf{n}_{2\ell}$ one of the ℓ waves (carrying the compressive deformation) lie in the $(001)_\gamma$ plane. The size d_s corresponds to the length of the square-cross section shortest edge of the $s-\ell$ cell, which defines the region of the loss of stability in the lattice during the formation of the main component of the layered (or twinned) structure; λ_s is the length of the s wave.

The conditions for reproducing the best regime for the activation of the $s-\ell$ cell in the region of the wave front of the CWP has the simple form

$$v_{1s} = v'_{2\ell}(\psi)\cos(\psi), \qquad (1)$$

where $v'_{2\ell}(\psi)$ is the projection of the velocity $v_{2\ell}$ on the $(001)_\gamma$ plane.

As shown in [9, 10], the strictly periodic layered structure that arises is characterized by a ratio of the

component volumes β that depends only on the parameter d_s/λ_s and on the direction of propagation of the wave responsible, on the mesoscale, for the compressive deformation in the CWP as follows:

$$\beta = \frac{4\frac{d_s}{\lambda_s}}{1 + \tan\psi - 4\frac{d_s}{\lambda_s}}. \quad (2)$$

The example shown in Fig. 3 corresponds to the ratio of component volumes $\beta = 2$.

However, one should keep in mind that the angle ψ is not arbitrary, but is dictated by the direction of the vector of elastic component of strain of a dislocation nucleation center. The nucleation center breaks the symmetry of the original lattice and reduces the energy and deformation barriers in the region where the excitation state originates.

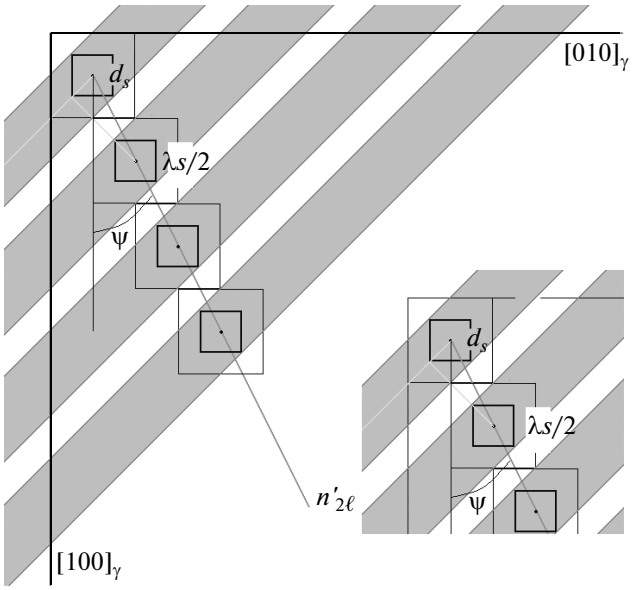

Fig. 3. Dynamic model of regular layered structure formation at $\beta = 2$.

2. REASONS FOR β_{tw} AND δ_{tw} VARIATIONS AND ESTIMATION OF RESPECTIVE VARIATIONS IN THE δ_s/λ_s PARAMETER

Below, we will consider the value of the angle ψ to be fixed, although it can vary with the varying of the initial excitation state area localization in a nonuniform elastic field of the dislocation nucleation center. The fact is that this change results in a change in the crystal habit plane. We are also interested in the twin components ratio variation at a constant habit plane in the bulk of the same crystal. Thus, it is obvious from (2) that the main influence on the β_{tw} value and, accordingly, on the δ_{tw} value, which is associated with the β_{tw} by the simple equation

$$\delta_{tw} = (\beta_{tw} + 1)^{-1}, \quad (3)$$

has the parameter d_s/λ_s.

The condition (1) of the exact time match between the propagation of *s* waves superposition along catheti of a triangle (shown in Fig. 2) and that of the ℓ wave (which carries compressive deformation) along the hypotenuse of the same triangle means that the *s* and ℓ oscillation phases in the center of the shortwave cell correspond to the deformation maxima. The overlap of their waves provides a strain level that exceeds the threshold value.

A deviation from this strict requirement, referred to in [10] as the "fine-tuning condition," is inevitable according to the following reasons. First, the $s-\ell$ cell may not be activated precisely when the shortwave displacements deformation maxima coincide. Second, a change in the λ_s wavelength associated with the transverse dimension of the $s-\ell$ cell can be accompanied by the nonfulfillment of the strict Eq. (1) because of the dispersion of the dependence $v_s(\lambda)$ of the speed of *s* waves, which will lead to an increase in the phase mismatch of the *s*- and ℓ waves during the formation of a twin structure. It is obvious that both of these reasons must appear in the variations in the parameter d_s/λ_s. Third, the existence of local medium inhomogeneities makes a reproducing fault in the $s-\ell$ cell possible at any stage of the growth of the main component of a twinned structure. Fourth, as a result of random fluctuations, it became possible to excite the $s-\ell$ cell with the best parameters for running the growth in the TS main component as compared to $s-\ell$ cells occurred due to the emission of wave beams of the previous growing TS main component.

Considering the variations in δ_{tw} and β_{tw}, it is necessary to check for independent arguments for determining some perfect values of $(\delta_{tw})_{id}$ and $(\beta_{tw})_{id}$ for a given habit plane according to the dynamic theory. Of course, these arguments are indeed existent. As shown in [10], the most rapid transition to finish (Bain) deformations corresponds to the relation

$$(\beta_{tw})_{id} = \frac{|\varepsilon_{2B}|}{\varepsilon_{1B}}, \quad (4)$$

where ε_{1B} and ε_{2B} are the principal tensile and compressive values of a Bain deformation tensor. Using the data of [3] for the Fe–22Ni–0.8C alloy, i.e., allowing for $\varepsilon_{1B} = \varepsilon_{3B} \approx 0.12011$ and $\varepsilon_{2B} \approx -0.17232$, from (4) and (3), we obtain $(\delta_{tw})_{id} \approx 0.4107$, $(\delta_{tw})_{id}$ is close to the central point of the δ_{tw} values observed range. As was already mentioned in the introduction, the values of $\delta_{tw} \approx 0.41$ also can be obtained according to the crystal geometric approach [1]. It is easy to see from Eq. (2) that, when $\tan\Psi = 1/3$, the values $\beta_{tw} = 1.5$ and $\delta_{tw} = 0.4$, which are close to perfect, correspond to $d_s/\lambda_s = 0.2$. Retaining Ψ by fixing the habit plane and reducing d_s/λ_s from 0.2 to 0.18, we can obtain from (2) and (3)

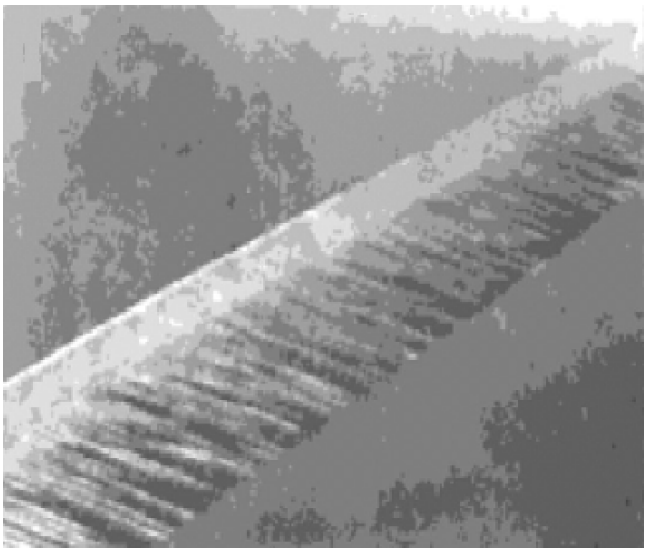

Fig. 4. Internal martensite crystals structure: (a) bright-field image (×24000) (Fig. 3.6 (a) from [4]).

$\beta_{tw} = 1.1739$ and $\delta_{tw} \approx 0.46$, the upper boundary of the observed variation instead of $\beta_{tw} = 1.5$ and $\delta_{tw} = 0.4$. The half deviation from $d_s/\lambda_s = 0.2$ leads to values of $\beta_{tw} \approx 1.7027$ and $\delta_{tw} = 0.37$, the lower limit of the interval for d_s/λ_s is 0.21.

3. ABSENCE OF TRANSFORMATION TWINS IN THIN PLATE-LIKE MARTENSITE CRYSTALS

Let us turn our attention to the experimental result given in [4], which consists in the observation of crystals without transformation twins together with twinned thin plate-like martensite crystals immediately after their activation by a strong pulsed magnetic field. Despite the relative rarity of these events, this fact is of fundamental importance for understanding the transformation mechanism. Indeed, from the standpoint of crystal geometry [1] transformation twins (ot systematic displacements) are necessary in order to initiate formation of crystals with habit planes $\{3\ 10\ 15\}_\gamma$. From the point of view of dynamical theory, the ℓ waves are responsible for the habit formation. Therefore, not only are variations in the twin component fraction possible, but also the complete absence of twinning. It is clear that the time interval required to select (near-perfect) phasing of s and ℓ vibrations in the initial excited state is reduced (limited by the pulse duration ((10^{-4} to 10^{-3} s) under pulsed exposure, at least compared with the relatively slow cooling alloys with compositions such that the start point of martensite transformation is below ambient temperature. However, the case of excited ℓ vibrations in the central area without shortwave fluctuations in the desired phase is quite possible. Consequently, the control wave process will not include shortwave components that stimulate the formation of the main twins component. Moreover, the impact of the magnetic field shifts the starting point of the transformation to the area of higher temperatures where the damping of short waves significantly increases, so the lack of the necessary phase matching of s and ℓ oscillations at the starting position will inevitably lead to the absence of the twin structure. Certainly, the lack of twinning leads to high levels of stresses, which are partially removed during subsequent one-sided lateral growth. In Fig. 4, taken from [4], the initial non-twinned crystal corresponds to the upper slim light part.

4. CONCLUSIONS

(1) An analysis of the variations in the twin component fraction speaks in favor of the ideas of the martensitic transformation developed in dynamic theory [5–10]. This theory not only naturally explains the presence of the optimal value of the parameter $\delta_{tw} = (\delta_{tw})_{id}$, but easily discloses probable physical reasons for the observed deviations from the $(\delta_{tw})_{id}$, including the case when transformation twins are absent.

(2) It is equally important that it is possible to form a strictly regular twinned structure as the ideal limiting case associated with the principle of the rapid realization of martensitic transformation.

(3) Our estimations showed that the range of d_s/λ_s scatter can be easily reconstructed using δ_{tw}. Then, considering the traditional theory for the development of dynamic theory, we state that the list of morphological features that make it possible to reconstruct the details of the dynamics of formation of martensite crystal is continuously updated.

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