

Dynamical Lattice State at the Initial Stage of Martensitic Transformation and Possibilities of its Physical Realization

V.V. Letuchev, S.V. Konovalov and M.P. Kashchenko

Professor M.P. Kashchenko, Holder of the Physics Chair, Ural State Wood Technology Academy, Sybirskiy Trakt, 37, 620032 Ekaterinburg, Russia

Principles of the physical simulation of conditions at the initial stage of γ - α martensitic transformation are formulated on the basis of the theory which synthesizes conceptions of the heterogeneous nucleation and the wave growth of martensite. The choice of the experimental method available to realize the artificial initiation of transformation is justified. Possible mechanisms of excitation of the hypersonic controlling waves by a single supershort laser pulse are presented. The information about perspectives of using the received results for alloys featuring the shape-memory effect is also presented.

1. INTRODUCTION

The physical realization of conditions corresponding to the initial stage of martensitic transformation (MT) in the original austenite lattice means (in the context of present communication) the artificial creation of object similar to the martensite nucleus. The following growth of the last one will cause the formation of macroscopic martensitic crystal (MC) in the austenitic volume. Thus by the man-made triggering there may be produced a single martensitic lamella and its dimensions (excepting the thickness) will be defined only by overall dimensions of the investigated specimen. Such object will allow to receive unique refined data about martensite properties. Another important consequence: the method of controlled initiation of MT gives a possibility to form a signal rigidly synchronized in time with the beginning of the martensitic lamella growth. The use of such reference signal opens perspectives to investigate in detail the separated stages of the MC and MC ensemble dynamics in the real time immediately during the MT process.

The experiments on the controlled initiation of MT demand a detailed information concerning both properties of the austenite lattice state corresponding to the MT initial stage and mechanisms maintaining the subsequent evolution of this state. Such information may be taken from the theoretical model which describes adequately all the set of MT observed features. The next problem to be resolved is the choice of experimental method allowing to carry out the controlled initiation.

2. γ - α MARTENSITIC TRANSFORMATION: PARTICULARITIES AND MECHANISMS

In this work the problem of initiation of the single MC growth is

considered for the γ - α MT in the Fe-31,5%Ni alloy single-crystals. The original high-temperature γ -phase (austenite) has fcc-lattice and the low-temperature α -phase (martensite) has bcc-lattice [1]. The transformation is characterized by the pronounced attributes of the first-order phase transition and proceeds as cooperative one. It is important to note that the specific (per unit of mass) volume of α -phase is more than one of γ -phase.

A martensite arises in the form of lamellas with a small ratio of thickness to the other linear dimensions. The lamella thickness is about 1 μ m. A lamella habit plane (an interphase boundary) takes 24 consistent orientations which are described by collection $\{3\ 10\ 15\}_{\gamma}$ (relative to the crystallographic axis of γ -phase). The martensite lamella formation at the MT process is accompanied by appearance of the relief on external surfaces that allows to register by optics the transformation. Often the MC set demonstrates the well defined order in the relative position. This particularity allows to say about the formation of MC ensembles.

MT in the Fe-31,5%Ni single-crystals exhibits brightly the athermal macrokinetics and may be classified as "explosive" transformation (a major volume proportion of martensite arises during the explosion). This particularity causes the well audible sound click at the moment of transition.

It should be noted specially that MC at the γ - α MT grows at the high rate. In accord with data received experimentally in works [2,3] the magnitude of this rate exceeds the longitudinal sound velocity.

γ - α MT obviously demonstrates the attributes of the first-order phase transition which allows to suppose that the stages of nucleation and MC growth take place. The martensite nucleation is considered to have a heterogeneous character and dislocations play the important role at this process.

Whole set of γ - α MT observed features may be correctly and consistently described within the scope of the approach which is based on synthesis of two conceptions: of the heterogeneous (near dislocation) nucleation and of the MC growth controlled by quasilongitudinal displacement waves. Experimental data about high (supersonic) rate of MC growth lead to the wave mechanism which is physically unalterative. The indicated approach in the most complete view is expounded in the monograph [4]. The work [5] represents a compact (but enough qualitative) interpretation of basic ideas and includes the new results and conclusions.

The theory points important both to understand the principles of modelling of lattice state on the MT origin stage and to carry out the MT artificial initiation are presented below.

MT starts from the excited state in the form of heavily elongated rectangular parallelepiped with the long opposite faces oscillating in pairs in antiphase. The orientation of parallelepiped is defined

by the triple of the mutually orthogonal vectors $\vec{\xi}_1, \vec{\xi}_2, \vec{\xi}_3$ (Fig.1).

The transformation in the parallelepiped volume will have started when amplitudes of oscillations in the directions $\vec{\xi}_1$ and $\vec{\xi}_2$ will reach

values ε_1^{th} and ε_2^{th} (threshold deformations) and besides the deformations will satisfy the conditions:

$$\varepsilon_1 > 0, \varepsilon_2 < 0, \varepsilon_3 \ll \varepsilon_1, |\varepsilon_2| \quad (1)$$

(tension, compression and small deformation in the directions $\vec{\xi}_{1,2,3}$).

The vector $\vec{\xi}_3$ lies in the weak-distorted (invariant if $\varepsilon_3 = 0$) plane favorable for the interphase contact. The energy liberated during transformation is spent partly for a generation of two hypersonic wave beams which propagate at the velocities c_1, c_2 (the wave normals: $n_1 = c_1/c_1, n_2 = c_2/c_2$). It is easy to see that the intersection line (as well as the area where the conditions (1) are fulfilled) of two wave fronts moves at the velocity $c = c_1 + c_2$. As a result the martensitic lamella grows at the velocity c . A mechanism of generation of two longitudinal controlling waves is based on the stimulated acoustic phonon emission by non-equilibrium 3d-electrons at the region separating γ - and α -phases [4].

In the case of the spontaneous γ - α MT the excited state is considered to arise by fluctuation in the well definite area near the rectilinear dislocation. In so doing, the vectors $\vec{\xi}_1$ are the eigenvectors of elastic deformation tensor in the indicated area. The corresponding eigenvalues ε_1 satisfies the conditions (1). In this area the energetic interphase barrier is lowered and the conditions favorable to arise the threshold fluctuation take place. Synthesis of two conceptions of the heterogeneous nucleation and of the wave growth leads to the additional conditions [5]:

$$n_1 \approx \vec{\xi}_1, \quad n_2 \approx \vec{\xi}_2, \quad (2)$$

$$c_2/c_1 \approx (\varepsilon_1/|\varepsilon_2|)^{1/2}. \quad (3)$$

It should be noted that $\varepsilon_1 > |\varepsilon_2|$ (as a result of increase of the specific volume during γ - α transformation) and $c_2 > c_1$, i.e. the compression deformation in the transformed region is effected by the wave propagating at the lower velocity.

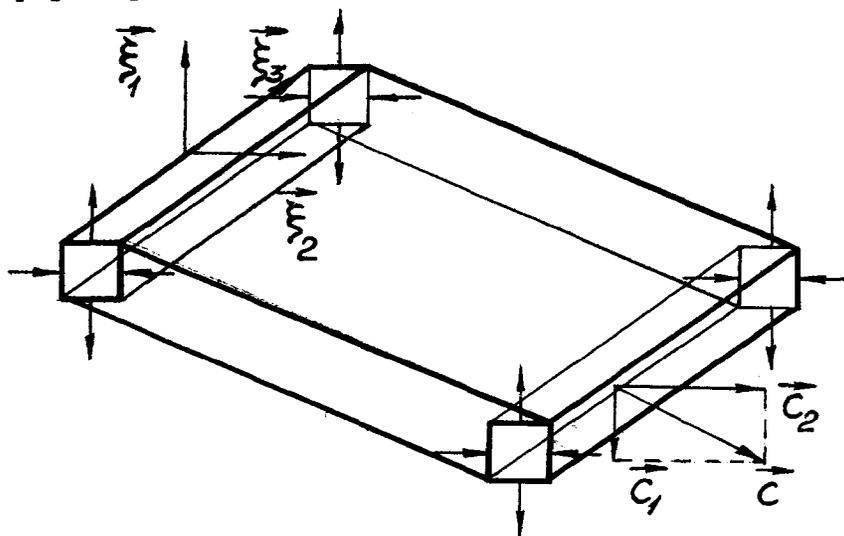


Fig.1. Scheme illustrating the martensitic lamella growth controlled by two longitudinal waves.

3. CONTROL OF γ - α MT

In accord with the above-mentioned theoretical statements to initiate

the γ - α MT it is necessary to model the initial excited state. The last one should be parallelepipedal in form and well definitely oriented relative to the crystallographic axes of γ -phase lattice (the parallelepiped orientation is specified by the vectors $\vec{\xi}_1$, $\vec{\xi}_2$, $\vec{\xi}_3$). The cross dimensions d of such parallelepiped is defined from the characteristic thickness of martensitic lamella (about $1 \mu\text{m}$), the oscillation frequency of its opposite faces lies at the hypersonic frequency interval (10-100 HHZ) [6], the oscillation amplitude has to be sufficient to create the threshold deformation $\varepsilon^{\text{th}} \approx 0,001$ [7]. It may be carried out e.g. by generation of two mutually orthogonal coherent waves with $1/2\lambda = d$. The sound wave intensity I necessary for the MT initiation may be easily estimated: $I = 2\varepsilon^{\text{th}}Gc \approx 2 \text{ TW/m}^2$, where G (modulus of elasticity) $\approx 200 \text{ HN/m}^2$ and c (velocity of longitudinal sound) $\approx 5 \text{ km/s}$ are taken for the Fe-31,5%Ni alloy [8]. In other words the wanted experiment on the sample with the work-surface area 10 mm^2 needs a generator of hypersonic (10-100 HHZ) oscillations with $\approx 2 \text{ MW}$ in power. Technical realization of mentioned parameters is possible by using the pulse sources only. It should be noted that the application of pulsed action is perfectly justified because the one-time deformation of transformed volume is quite sufficient to initiate the MT in accordance with the condition (1). In this case the duration of acoustic pulse (5-50 ps) is defined by a half of period of controlling oscillations. Further, the necessity of ultimate localization (to initiate the single MC) apparently keeps out the use of gas gun while it is the instrument available for the direct transformation of the kinetic energy to the sound oscillation energy. Besides, in this case it is difficult to expect the generation of hypersonic acoustic pulses with the amplitude sufficient to create the threshold deformation. At present the problem of excitation of high-intensity picosecond acoustic pulses by the supershort pulse laser can be considered as resolved one [9]. Application of the light radiation permits to concentrate an energy in the volume with dimensions about a wavelength (for a visible light $< 1 \mu\text{m}$) and to satisfy the theory demands. The results of first successive experiments on the γ - α MT initiation in the Fe-31,5%Ni single crystals by unit laser pulse (pulse duration: $\approx 20 \text{ ps}$, wavelength: $0,63 \mu\text{m}$, energy: $\approx 5 \text{ mJ}$) are presented in [10]. The work face was parallel to the crystallographic plane $(001)_{\gamma}$ which had the smallest angle (about 2°) with the long axis $\vec{\xi}_3$ of martensite nucleus. In the same time the vector $\vec{\xi}_1$ is close to the direction $[001]_{\gamma}$ and the angle φ between $\vec{\xi}_2$ and the one of the four-fold axes lying in the plane $(001)_{\gamma}$ is about 17° . Since the wave normals $n_{1,2}$ do not coincide in direction with the crystallographic symmetry axes the controlling waves are quasilongitudinal. The laser radiation was focused on the irradiated surface by a cylindrical lens therefore the laser action trace appeared as an elongated strip (the ratio of length to width about 500). The action area was similar in the form (taking into account a finite depth of radiation penetration) to the elongated parallelepiped. A geometry of experiment is shown on the Fig.2. The conducted experiments have corroborated that the γ - α MT may be initiated by the single picosecond laser pulse. On the other hand it was impossible to initiate a transition for the significant deviation of the specimen temperature T_{sp} from the MT start temperature M_s . The typical difference value $T_{\text{sp}} - M_s \approx 4 \text{ K}$. Evidently, the warming of

volume absorbing an energy (a favorable factor at the reverse α - γ MT) retards the γ - α MT initiation because the moving from M_g is accompanied by the growth of the energetic interphase barrier.

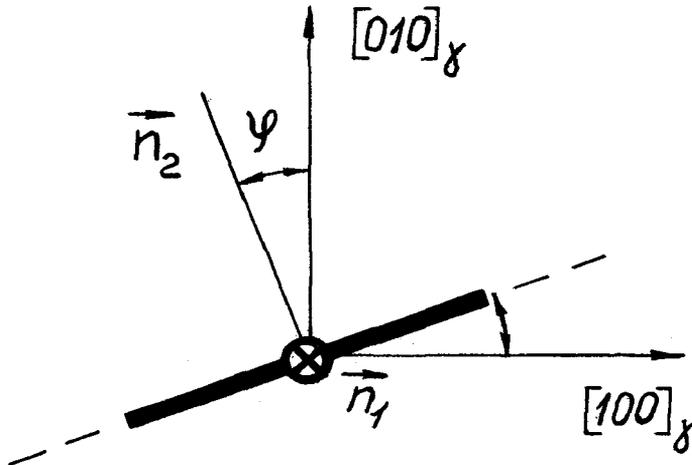


Fig.2. The orientation of the normals of the waves generated by the laser pulse. The bold line shows the laser trace. Sign \otimes shows the orientation of the wave normal $n_1 \approx [001]_\gamma$.

4. GENERATION MECHANISMS OF CONTROLLING WAVES AT THE LASER PULSE ACTION

The rectangular shape of the laser action trace on the tested specimen face allows to apply (for a qualitative interpretation) the analytical solution of problem on the indentation of the plane stamp which is infinite in length and finite in width [11]. The given problem is resolved within the scope of the elasticity dynamic theory for the predetermined law of the stamp movement. Fig.3 shows the fronts of waves excited by indented stamp in the half-unbounded isotropic medium occupying the half-space $z > 0$ at some moment $t > 0$. Deformation of volume under the stamp is defined by superposition of displacements which are created by the plane longitudinal wave $W_{p,1}$, two cylindrical longitudinal waves $W_{c,1}$ and two cylindrical transverse waves $W_{c,t}$ [11]. The phase velocities of longitudinal (plane and cylindrical) waves are equal and exceed ones of transverse waves. In the case of the pulse action it is necessary to speak actually about acoustic pulses $W_{p,1}$, $W_{c,1}$, $W_{c,t}$. A comparison of Fig.1 with Fig.3 shows that the initiation

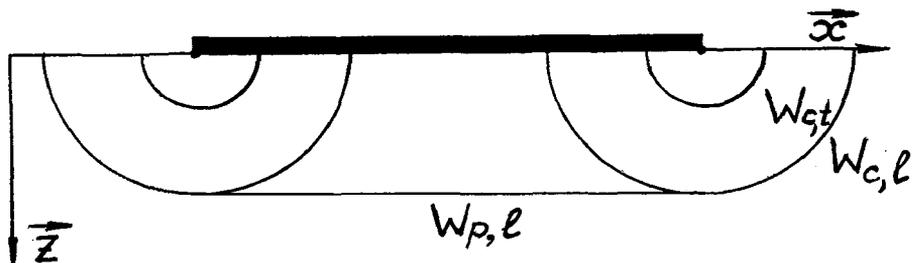


Fig.3. The fronts of the waves excited by the moving plane stamp in the isotropic medium. The bold line shows the cross-section of the stamp.

needs tension in the direction z and compression in the direction x (Fig.3). Areas with such deformation may be realized when the acoustic pulses $W_{p,1}$ and $W_{c,1}$ are bipolar, i.e. have both the compression stage and the tension one. Obviously, the tension deformation (ε_1) has to be created by the pulse $W_{p,1}$ and the compression one (ε_2) - by the pulse $W_{c,1}$.

For cylindrical waves the compression and tension areas are known [12] to be obligatory. In the case of the plane wave the tension area is formed only after the compression pulse (formed by an external action) will be reflected from the free-stress specimen boundary. The compression pulse is created in surface layer about $0,1 \mu\text{m}$ in thickness as result of both the thermoelasticity mechanism [9] and the recoil momentum of reflected photons and evaporated atoms (at the atom evaporation regime the contribution of the last mechanism is determinant). Certainly, the specimen surface may be regarded as free one only after the irradiation process will be completed. Thus, in the case of the rectangular laser action trace there are two areas (near the specimen face) where the conditions demanded for the MC growth initiation may be realized.

The presented interpretation of creation of excited state by the laser action adjusts essentially the treatment proposed in works [5,10] where one of the two controlling waves was supposed to arise as a result of the Poisson's effect.

As an conclusion the following should be noted. According to the calculations [13,14] it may be expected a stimulated initiation of martensite growth in the Cu-Zn and Ti-Ni-Cu alloys by the pulse laser action. The positive results of similar experiments will give evidences for an extension of the theory conclusions [4] to the MT in alloys exhibiting the shape-memory effect.

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