New directions in martensite theory

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Abstract

Advances in materials science, applied mechanics, physics and mathematics offer new opportunities for the science and engineering of martensitic materials. A systems approach to multilevel dynamic microstructure emphasizes the importance of distributed defect hierarchy in predictive control of desired behaviors. Total energy electronic calculations and Landau free energy functions describe nonlinear energetics of lattice deformations with atomic shuffles, and incorporation of non-local strain gradient energies in Landau–Ginzburg models has allowed numerical simulation of homogeneous and heterogeneous nucleation as well as semi-coherent growth and twin variant conversion. Analysis of multiscale defect interactions addresses growth in a plastic matrix and the nature of nucleation site potency distributions in both thermoelastic and non-thermoelastic systems. Predictive design theory incorporates macroscopic constraints in polycrystals and thin films. Biological molecular martensites underlying infection mechanisms in HIV and influenza viruses offer a fertile area for adaptation of martensite theory. © 1999 Elsevier Science S.A. All rights reserved.

Keywords: Martensite theory; Nucleation and growth; Multilevel dynamic microstructure; Biological molecular martensite

1. Systems: dynamic hierarchy

Modern numerical methods paced by rapidly advancing computational power have opened the way to a far more realistic theoretical treatment of the complexity of materials behavior. The resulting enhanced appreciation of natural complexity has fostered renewed interest in the ‘systems’ view of materials proposed by the late C.S. Smith [1], who recognized the inevitable hierarchical nature of materials structure, with strong interactions amongst length scales, and an interplay between perfection and imperfection involving a ‘duality’ whereby structure can be equivalently regarded as a hierarchy of three dimensional space filling domains of relative perfection or a hierarchy of lower-dimensional defects/imperfections which bound them. Smith warned of a cultural bias toward perfection, and emphasized the importance of defect hierarchy in the willful control of materials behavior. His view also acknowledged an intrinsic dynamic nature, whereby a spectrum of relaxation times associated with structural hierarchy assures an intrinsic path-dependent nonequilibrium structure of real materials. This inherent complexity sets limits on the degree of predictability of materials behavior from ‘first principles’ approaches, and Morris Cohen [2] has eloquently argued the importance of a ‘reciprocity’ between the deductive cause/effect logic of reductionist analysis and the inductive goal/means logic of systems synthesis whereby useful insights such as structure/property relations can be distilled from natural complexity by probing structure from the viewpoint of specific desired properties.

This philosophy has formed the basis of a systems approach to computational materials design which has been successfully applied to martensitic steels over the past decade, and is now being extended to all classes of materials [3]. The pioneering application in martensites is due largely to an early scientific appreciation of complexity in martensitic systems. Current design research aimed at acceleration of the full materials development cycle emphasizes (a) integration of microstructural evolution in process models supporting a design-for-processability approach anticipating process scaleup; and (b) a probabilistic science quantifying the role of distributed defect hierarchy, especially in structure/property relations, for predictive control of variation to accelerate materials qualification. This review assesses the evolution of martensite theory in the context of this changing materials engineering environment.
Consonant with this view, Fig. 1 depicts the spatio-temporal hierarchy of first-order displacive (e.g., martensitic and bainitic) transformations. Blocks at the left represent interactive levels of structure both preceding and generated by the transformation, while blocks at the right denote a sequence of dynamic phenomena interacting with these structural levels. As denoted by the interconnections, initial nucleation is sensitive to interfacial defects generated by the processing history, determining the initial number density $N_i$ of heterogeneous nucleation sites and the critical driving force at which they operate. The latter determines the dynamics of unit growth events and influences the degree of dislocation substructure generation determining subunit morphology (plate/lath) and the initial average particle volume $V_o$. The character of growth in turn establishes the elastic or plastic fields governing the number density $N_A$ and potency of autocatalytic nucleation sites, which evolve with phase fraction $f$. The character of autocatalytic nucleation in turn establishes the initial geometry of variant pairs influencing the cooperative multivariant growth of higher level groups (packet/sheaf) determining the evolution of average particle volume $V(f)$. These are also influenced by the transgranular spread of transformation in polycrystals, as well as other macroscopic constraints of component shape and external boundary conditions. On the finest scale denoted, solutes and other fine scale defects exert an influence on several levels, primarily through interfacial friction. Progress in martensite theory has addressed each of these aspects, with due attention to both hierarchies of space-filling domains and space-dividing defects.

An overall assessment of the current state of computational materials science is that simulations have demonstrated remarkable success in reproducing aspects of observed natural complexity. In the spirit of Cohen's reciprocity, the challenge for the near future is to purposefully exploit the capabilities of these techniques (allowing parametric studies not accessible by experiment) to yield new insights offering predictive control of specific desired behaviors.

2. Physics of lattice, deformations and interfaces

A major advance in theoretical capability has been the improved accuracy of ab initio electronic quantum mechanical calculations of the energy differences between parent and product lattices, and the interpretation of their origins in terms of band structure and bonding. The approach offers the potential for prediction of new directions in alloy chemical composition for control of desired phase stability, which has yet to be significantly exploited. A further application of these methods, which has already had significant impact on martensite theory, is the prediction of the nonlinear energetics of homogeneous lattice deformations between structures. For relatively high symmetry strain paths through energy saddle points, calculations have included alkali metals [4,5], Fe and it alloys [6–8], Cu-base alloys [7] and TiNi alloys [9,10]. The lattice deformation calculations define energy density barrier heights important to coherent interfacial energy, and identify conditions where energy surfaces are cusped [6] rather than smooth. Most important to issues of competing transformation mechanisms, calculations as a function of pressure identify critical driving forces for lattice instabilities [6].

In transformations involving atomic shuffle displacements within the unit cell as well as lattice strains, energy calculations for all possible combinations of shuffle displacements and strains along a lattice deformation path can become prohibitively complex. An especially useful tool in this case is the development of Landau free energy functions which incorporate crystal symmetry constraints and define external configurations. Coefficients of functions thus defined can be calibrated by a reasonable number of electronic total energy calculations. Such Landau functions have now been derived for specific structural transformations involving multiple shuffle-based order parameters [11–13]. An important advance bringing this approach to technologically important martensitic systems is the recent analysis by Barsch [13] of the Landau order parameters of the transformations from B2 to the R, B19, and B19' structures in TiNi and AuCd alloys.

Fig. 2 summarizes the symmetry defined shuffle and strain order parameters for each group → subgroup transformation in these systems. Detailed analysis of available phonon dispersion curves in both the TiNi and AuCd systems has allowed development of analytical Landau free energy functions versus temperature for the B2 → R transformations, and functions are being

![Fig. 1. Flow-block diagram of martensitic transformation as a multi-level dynamic system.](image-url)
Structural Transformations in NiTi & AuCd

Fig. 2. Summary of shuffle and strain order parameters for group/subgroup transformation in TiNi and AuCd alloys. After Barsch [13].

developed for the larger strain B2 → B19 and B2 → B19' martensitic transformations [14].

A versatile method for the bridging of length scales within the structural hierarchy of Fig. 1 is the application of nonlocal continuum models. Detailed calculations at a fine scale can be ‘homogenized’ by gradient energy coefficients to define size-dependent constitutive laws to treat coarser-scale problems. The approach is now seeing broad application in computational materials science via the ‘phase field’ approach to simulation of phase transformations as pioneered by Cahn and Hilliard [15]. Within this realm, martensitic transformations represent perhaps the most rigorous application of the approach, building on the seminal research of Barsch and coworkers developing Landau–Ginzburg models with symmetry-constrained gradient energy coefficients deduced from measured phonon dispersion curve anomalies in specific martensitic systems [16–18], recently extended to incorporate gradient contributions of shuffle parameters [12]. In strongly first-order systems without such anomalies, gradient energy coefficients can be deduced from direct observation of interfacial core widths by HREM lattice imaging. This requires special systems with near-rational invariant lines to allow edge-on viewing of a semicoherent interface in a low index direction. This has allowed detailed analysis of interfacial core displacement fields for the B2 → 18R transformation in CuZn [19] and more recently the FCC → BCT transformation in an Fe alloy [20].

Interfacial energies, particularly for the internal twin boundaries of martensitic substructures, have been calculated both from variational solutions of the Landau–Ginzburg models [16–18], and by direct calculations by quantum electronic methods [21,22]. Greater accuracy of the latter methods is now being achieved by addressing nonlocality at the electronic level as well. A modification of the full potential augmented plane wave (FLAPW) method replacing the local spin density approximation (LSDA) with a generalized gradient ap-
proximation (GGA) has for the first time predicted the correct relative energies and lattice parameters of the FCC and BCC structures of Fe from an ab initio calculation [23], and is now being applied to BCC incoherent twin boundaries [24]. The new predictive capabilities in the physics of phase stability and lattice deformations offer a fertile ground for inventing new martensites from a very fundamental perspective. New devices such as microactuators based on traditional thermally induced martensitic transformations suffer limitations of heating and cooling processes. An ‘electromartensite’ switched on and off directly by an electric field would offer greater efficiency, but large strain ferroelectric martensites are constrained by the intrinsic brittleness of insulators. ‘Magnetoemartensites’ driven by magnetic fields can offer the better mechanical properties of metallic systems; prototype systems show promise [25], and detailed materials design considerations have been explored by R. James [26].

3. Nucleation

A topic which has particularly benefited from the nonlocal continuum Landau–Ginzburg models is the treatment of martensitic nucleation, the first process in Fig. 1. Compared to finite element methods, new meshless numerical methods such as the element-free Galerkin (EFG) method [27] have proved to be more efficient in the computation of strain gradients to find variational solutions within the non-local models. A first problem to test this approach has been the modeling of homogeneous nucleation at high driving forces where an issue of principal interest is the degree of nonclassical behavior, characterized by critical nuclei of reduced strain amplitude. Chu and Moran [28] have rigorously treated the case of a simple 2D coherent shear transformation and demonstrated reduced strain amplitude and divergence of critical nucleus size and interfacial width on approaching a lattice instability, similar to the Cahn–Hilliard treatment of nonclassical nucleation in decomposing fluids [15]. Based on these solutions, an approximate treatment was developed to describe the energetics of nonclassical homogeneous nucleation in 3D systems including the FCC-BCT transformation in steels [29]. For the latter case, the model was fit to measured critical driving force data for homogeneous martensitic nucleation in small particle experiments conducted in the Fe–Co system [30]. The solid curve in Fig. 3 represents the model prediction for fully coherent homogeneous nucleation with a coherent interfacial energy corresponding to 20 mJ/m² in the classical limit. Based on the electronic calculations of lattice stability limits [6], the measured nucleation critical driving forces are at approximately 70% of the critical driving force for instability, and the new model here predicts that departures from fully classical behavior reduce the nucleation critical driving force by 20% from the classical limit (upper dashed curve). The previous rigorous calculations indicate that the critical nucleus strain amplitude is still within 90% of classical at this level of driving force.

The homogeneous nucleation critical driving forces of Fig. 3 are seven times higher than for nucleation under normal conditions, which is well known to be controlled by heterogeneous nucleation. Observed nucleation sites are generally linear defects with dislocation character, typically partially stabilized by interaction with interfaces (e.g. [31]). Groups of lattice dislocations were first proposed to model such defects in 1949 [32], and have been employed in detailed dislocation models of heterogeneous nucleation [33]. The latter have demonstrated that barrierless nucleation at such defects is preceded at lower driving force by the formation of local martensite embryos, consistent with the ‘pre-existing embryo’ hypothesis proposed by Kaufman and Cohen in 1958 [34]. Linear elastic dislocation models are inadequate to treat the earliest stage of the process, and this has now been addressed by Reid [35] using the nonlocal Landau–Ginzburg models and EFG method. A group of three lattice dislocations in the form of a finite tilt boundary segment (equivalent to a wedge disclination dipole) is embedded in the continuum, representing the dislocations as displacement gradient source functions continuously distributing the Burgers vector content over the scale of a lattice vector. The computed strain field at the upper right of Fig. 4 is obtained for a linear elastic material with the parabolic energy–strain curve shown at the upper left. The lower figures show the computed behavior for the nonlinear Landau–Ginzburg model of a simple coherent shear transformation at a high temperature corresponding to the instability point of the martensite phase. At this

![Fig. 3. Critical driving force for homogeneous nucleation (normalized to instability driving force) for FCC-BCT martensitic transformation in defect-free small particles [30]. Solid curve is fit of nonclassical coherent nucleation; dashed curve is classical limit [29].](image-url)
extreme temperature, a substantial embryo of the fully formed martensite is already stabilized at the defect. The result is in sharp contrast to the alternative proposal of a 'strain embryo' [32] or 'localized soft mode' [36] mechanism whereby a highly strained region collapses to the martensite structure at the $M_s$ temperature. The rigorous calculation shows that the 'soft mode' is already 'frozen' into the product structure well above the $M_s$ temperature, in a process closely resembling a defect dissociation. Additional calculations have revealed how the embryo can be further stabilized by interaction with a nearby free surface [37].

The nonlocal Landau–Ginzburg models aided by new numerical methods have provided long-sought quantitative answers regarding the two extremes of nonclassical homogeneous nucleation near a parent phase instability, and classical heterogeneous embryo formation near the martensitic phase instability. Further application to 3D problems such as FCC-BCT heterogeneous nucleation with varying states of coherency promises further insights.

4. Growth

Addressing the second unit process of Fig. 1, Wang and Khachatryan [38] have employed the time dependent Ginzburg–Landau (TDGL) equation, incorporating a linear-viscous dynamic response, in the 3D dynamic simulation of a cubic-tetragonal martensitic transformation with internal shuffles (improper ferroelastic) giving the sequence of structures depicted in Fig.
5. Starting from a supercritical embryo of arbitrary shape, the detailed simulation predicts the dynamic growth form of an internally twinned plate which is strikingly similar to the oblate spheroidal semicoherent embryo assumed by Kaufman and Cohen [34] and Knapp and Dehlinger [39] and predicted by the growth dynamic model of Raghavan and Cohen [40].

Relevant to the fourth process of multivariant growth in Fig. 1, the Wang–Khachaturyan simulations also treat multivariant microstructural evolution in the limiting case of semicoherent homogeneous nucleation. Detailed analysis of such simulations is a fertile area for further research on multivariant growth, and some analysis of the kinematic constraints in multivariant interactions has been initiated [41]. For the case of mechanically induced transformation, Roitburd [42] has extended his theory of polydomain microstructures incorporating the coherent thermodynamics of Larese and Cahn [43]. With phase fraction and variant fractions as primary state variables, the evolution of multivariant microstructure under displacement control is predicted as a series of thermomechanical equilibrium states for well-catalyzed (easy nucleation) systems at high stresses.

Experimental characterization of multivariant microstructural evolution has centered on the evolution of mean plate volume with phase fraction $\bar{V}(f)$ as a primary input into kinetic theory [44]. Extensive stereological study of nonthermoelastic plate martensites in ferrous alloys has shown a two-stage process in which initial grain-to-grain spreading of transformation characterized by a constant $\bar{V}$ is followed by an intragranular filling-in by finer plates characterized by a reciprocal power law. Preliminary measurements in a thermoelastic Fe–Pt alloy suggested a nonmonotonic behavior of $\bar{V}(f)$ [45], but a recent more thorough study in a coarse-grained thermoelastic TiNi alloy has given the same monotonic behavior as nonthermoelastic systems except for an overall finer plate size [46]. It is surprising that, despite the high interfacial mobility retained in thermoelastic systems, overall evolution of $\bar{V}(f)$ is similar to nonthermoelastic systems where growth units are frozen. This implies a dominance of universal geometric factors [47]. A deeper understanding of observed $\bar{V}(f)$

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Fig. 5. Simulation of growth of supercritical semicoherent (internally twinned) martensitic embryo in nonlinear nonlocal continuum model. Wang and Khachaturyan [38].
behavior awaits more detailed analysis of multivariant growth simulations.

The model assumptions of the unit growth simulation of Fig. 5 correspond to a thermoelastic system. A preliminary model of unit growth dynamics in nonthermoelastic systems has demonstrated the important role of (size and rate dependent) plastic accommodation of the transformation strain in governing the technologically important lath/plate morphological transition in steels [33,48]. Working within a mesoscopic continuum nonequilibrium thermodynamic framework [49], Levitas [50] has initiated more rigorous finite-element simulations of such unit growth in a plastic matrix. Contours of computed accumulated plastic strain for directional growth of a martensite lath are represented in Fig. 6. Calculating the incremental work of elemental growth steps offers insights into the evolution of morphology in a plastic environment. The behavior is found to be strongly path dependent, and nonlocal plasticity models are being adopted to more realistically treat size-dependent plastic flow at the 0.1 μm length scales of interest.

5. Defect hierarchy: distributed systems

Consistent with Smith's vision of the importance of defect hierarchy in materials behavior and the current need for probabilistic structure/property theory to efficiently control variation in modern materials engineering as discussed in Section 1, martensitic transformations may represent the best developed example of quantitative analysis of defect hierarchy for prediction of macroscopic behavior. Spanning the hierarchy of Fig. 1, modeling and experiment have quantified the roles of fine scale defects on both thermal and athermal components of interfacial mobility [51,52] and their dependence on alloy composition and plastic prestrain [53,54], as well as the distributions of initial and autocatalytic nucleation sites which dominate the evolution of transformation under cooling or stress [55–58].

While it is the nature of states of perfection to be uniquely valued, it is an inherent characteristic of imperfection to be distributed in nature. The study of heterogeneous martensitic nucleation has naturally emphasized the form of defect potency distributions. Small particle experiments have defined the potency distribution of initial nucleation sites in terms of critical driving force \( N_0(Ag) \) and analysis in term of heterogeneous nucleation theory has demonstrated that the distribution with respect to a defect size parameter \( N_v(n) \) is of exponential form in both metals and ceramics [55,57]; extension to macroscopic polycrystals by sensitive acoustic emission experiments has measured the grain size dependence of the distribution amplitude [56]. Fitting of stereological data for the evolution of plate number density in Fe-base alloys indicates that the number density of autocatalytic sites is of the form \( N_\lambda = pf \) [44], and more thorough analysis incorporating the exponential initial site distribution reveals that the autocatalytic potency distribution \( p(n) \) is well described by a normal distribution [58]. The relative potency of the two distributions determines smooth versus burst transformation modes, and probability functions defined by the initial potency distribution predict observed variation and sample-size dependence of the burst temperature [56]. Preliminary modeling of the evolution of phase fraction \( f \) with temperature in ferrous alloys with lath martensite morphology [59] indicates that a normal potency distribution of autocatalytic sites \( p(n) \) also applies if \( \bar{V}(f) \) takes the same form as for plate martensites, but the direct measurement of \( \bar{V}(f) \) in the very fine lath microstructures is difficult.

The recent extension of quantitative stereological studies to thermoelastic TiNi [46] indicates that the autocatalytic potency distribution \( p(n) \) is also unimodal and reasonably approximated by a normal distribution as represented by the cumulative distribution curve of Fig. 7. That the stress field of a plate periphery should serve as a potent nucleation site with a characteristic potency defining a distribution mode is not surprising, but more quantitative insight into observed behavior awaits more detailed analysis of 3D computer simulation of multivariant transformation. Preliminary modeling of the evolution of phase fraction \( f \) with temperature in ferrous alloys with lath martensite morphology [59] indicates that a normal potency distribution of autocatalytic sites \( p(n) \) also applies if \( \bar{V}(f) \) takes the same form as for plate martensites, but the direct measurement of \( \bar{V}(f) \) in the very fine lath microstructures is difficult.

Some insight into the nature of autocatalytic defects can be gleaned from theoretical modeling of martensitic interfacial junctions [60], and the simulation of twin
variant conversion in stressed martensitic microstructures [61,62]. For the latter case Killough and Kohn [61] have used a TDGL-type model to generate a fully transformed multivariant microstructure via a continuous quasimartensitic instability, and then studied details of stress-induced twin nucleation within this microstructure for comparison with twin 'tip splitting' observations conducted in Cu–Al–Ni [62]. Such a simulated event is represented in Fig. 8. A twin band tapering from its $K'$ plane intersects another band on the nearly orthogonal $K''$ plane to spontaneously generate a defect with the same wedge-disclination dipole character as the nucleation site of Fig. 4. The stress-induced formation of a twin embryo in this environment as shown in Fig. 8 is strikingly similar to the martensitic embryo formation of Fig. 4. While Fig. 4 models a rare initial nucleation site inherited from the complex processing history of the parent phase, Fig. 8 represents an inherent defect generated by multivariant transformation. Further detailed analysis of simulated microstructures like Fig. 8 could generate theoretical nucleation site potency distributions for comparison with experiment, ultimately offering more predictive control of the distributions which pace the macroscopic evolution of transformation with increasing driving force.

6. Constrained systems

Reaching to the higher levels of structure in Fig. 1, detailed considerations of the intergranular compatibility constraints in polycrystalline materials have employed a modified Taylor analysis to predict from lattice deformation symmetry the relative recoverable shape memory strains in a range of martensitic systems [63]. A recent extension demonstrates that the relatively high recoverable strains in TiNi alloys compared to Cu-based memory alloys is associated with crystallographic texture, and desirable textures for improved properties are predicted [64].

As denoted by the highest level of structure in Fig. 1, macroscopic component shape and surface boundary conditions can also constrain the evolution of multivariant microstructures, particularly the later stage processes of Fig. 1. Thin films with both free and constrained surfaces can constrain transformation at quite microscopic levels as well. Early experiments on ferrous martensitic transformations in thin films constrained by substrates demonstrated a wide range of crystal kinematic conditions compared to transformation in the bulk; the new conditions were shown to be consistent with invariant line strain (ILS) transformation with invariant lines defined by the intersection of the 'Bain cone' of undistorted lines with the plane of the film [65]. Roitburd [66] has recently applied his polydomain theory to multivariant microstructural evolution in constrained thin films, treating interactions with temperature dependent self stress associated with film–substrate thermal expansion mismatch. The model gives a series of local thermomechanical equilibrium polyphase polydomain states with a heating–cooling path dependence, reproducing essential features observed in TiNi films on Si. A kinematics-based theory incorporating elastic and surface energies by Bhattacharya and James [67] predicts that even 'released'
thin films will adopt ILS single-variant growth units, and conditions for formation of 'tunnel' and multivariant 'tent' morphologies are specified as a basis for design of efficient microactuators.

7. Biological systems: molecular martensite?

As first reported at ICOMAT-82 [68], biological protein cylindrical crystals undergo martensitic transformations to perform vital life functions in viruses and bacteria. In the case of the T4 bacteriophage, a virus that infects *Escherichia coli* bacteria, such transformation provides a tail-sheath contraction mechanism allowing the virus to inject its DNA into the bacterium. Analysis of the transformation kinematics accounting for constraints of 2D cylindrical symmetry identified a transformation shear strain of 120% coupled to a volume contraction of 40%. The transformation was shown to rigorously conform to the formal definition of martensitic transformations as proposed at ICOMAT-79 [69] and reassessed at ICOMAT-95 [70]. Subsequent work has assessed evidence for similar transformations in higher organisms [33].

Recently the structure of the gp41 subunit of the envelope glycoprotein of the human immunodeficiency virus (HIV) has been determined to have the helical trimer structure represented in Fig. 9 [71]. The subunit is known to be responsible for fusion of viral and cellular membranes, allowing release of viral contents into the host cell as an essential component of viral infection. A strong resemblance of the gp41 structure to that of the bistable hemagglutinin (HA) protein of influenza virus has led to the proposal that the gp41 fusion mechanism in HIV infection is the same as a displacive transformation 'harpoon mechanism' established in the influenza case [72]. The latter is represented schematically in the diagram of Fig. 10. In the 'native' state of the HA trimer at the left, part of the protein is in the conformation of a nonhelical loop folded into the core of a 'coiled coil.' On transforming to the 'fusogenic' state at the right, the entire trimer converts to the coiled coil configuration (as in Fig. 9 for the HIV case) extending the end by 100 Å during membrane fusion.

The transformation is clearly displacive in character, involving a large distortion. Despite the 3-fold rotational symmetry, the trimer lacks the translational symmetry to be classed as a crystal, and in that sense the transformation can not be formally classed as martensitic. Acknowledging the strong similarities, however, it is proposed that such transformations be called 'molecular martensities' (by analogy with 'liquid crystals') to encourage theoretical investigation of the applicability of martensitic concepts. Available information on the hydrophobic and hydrophilic components of the molecules offers insight into the origin of phase stability, and thermodynamic information exists in established phase boundaries with respect to pH and temperature for the influenza case [72]. Insights into nucleation path and dynamics may be fruitful in devising methods to prevent or disrupt the transformation. Consideration of detailed molecular architecture and phase stability has already led to speculation on small molecule inhibitors for an 'austenite stabilization' approach to defeating HIV infection [71].

Acknowledgements

Research on martensitic transformations at Northwestern University is sponsored by the National Science Foundation under Grant DMR-9500122. Many of the ideas presented here arose from discussions at a Martensite Theory Workshop held at Northwestern in June, 1998. Participants included G. Barsch (Penn State

Fig. 9. Helical trimer structure of gp41 subunit of HIV envelope glycoprotein believed to undergo large-strain displacive transformation [70].

Fig. 10. Representation of two structural states of influenza hemagglutinin (HA) protein involved in 'harpoon mechanism' of cell infection [71].

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