결정미소역학 (Crystal Mechanics)

Lecture 10 – Deformation in martensitic transformation

Ref : 1. Martensitic Transformation, Z. Nishiyama *et al*., 1978, Chapter 6
2. H.N. Han *et al*., “A model for deformation behavior and mechanically-induced martensitic transformation of metastable austenitic steel”, *Acta Mater.*, 52, 5203 (2004)
3. H.N. Han *et al*., “Crystal Plasticity Finite Element Modelling of Mechanically Induced Martensite Transformation (MIMT) in Metalstable Austenite”, *Int. J. Plast., 26, 688* (2010)

Heung Nam Han
Associate Professor
School of Materials Science & Engineering
College of Engineering
Seoul National University
Seoul 151-744, Korea
Tel : +82-2-880-9240
email : hnhan@snu.ac.kr

Martensite Transformation

The name martensite is after the German scientist Martens. It was used originally to describe the hard microconstituent found in quenched steels.

Many materials other than steel are now known to exhibit the same type of solid-state phase transformation, known as a martensitic transformation, frequently also called a shear or displacive transformation. Martensite occurs in, for example, nonferrous alloys, pure metals, ceramics, minerals, inorganic compounds, solidified gases and polymers.

Composition	M_S / K	Hardness HV
ZrO_2	1200	1000
Fe–31Ni–0.23C wt%	83	300
Fe–34Ni–0.22C wt%	< 4	250
Fe–3Mn–2Si–0.4C wt%	493	600
Cu–15Al	253	200
Ar–$40N_2$	30	

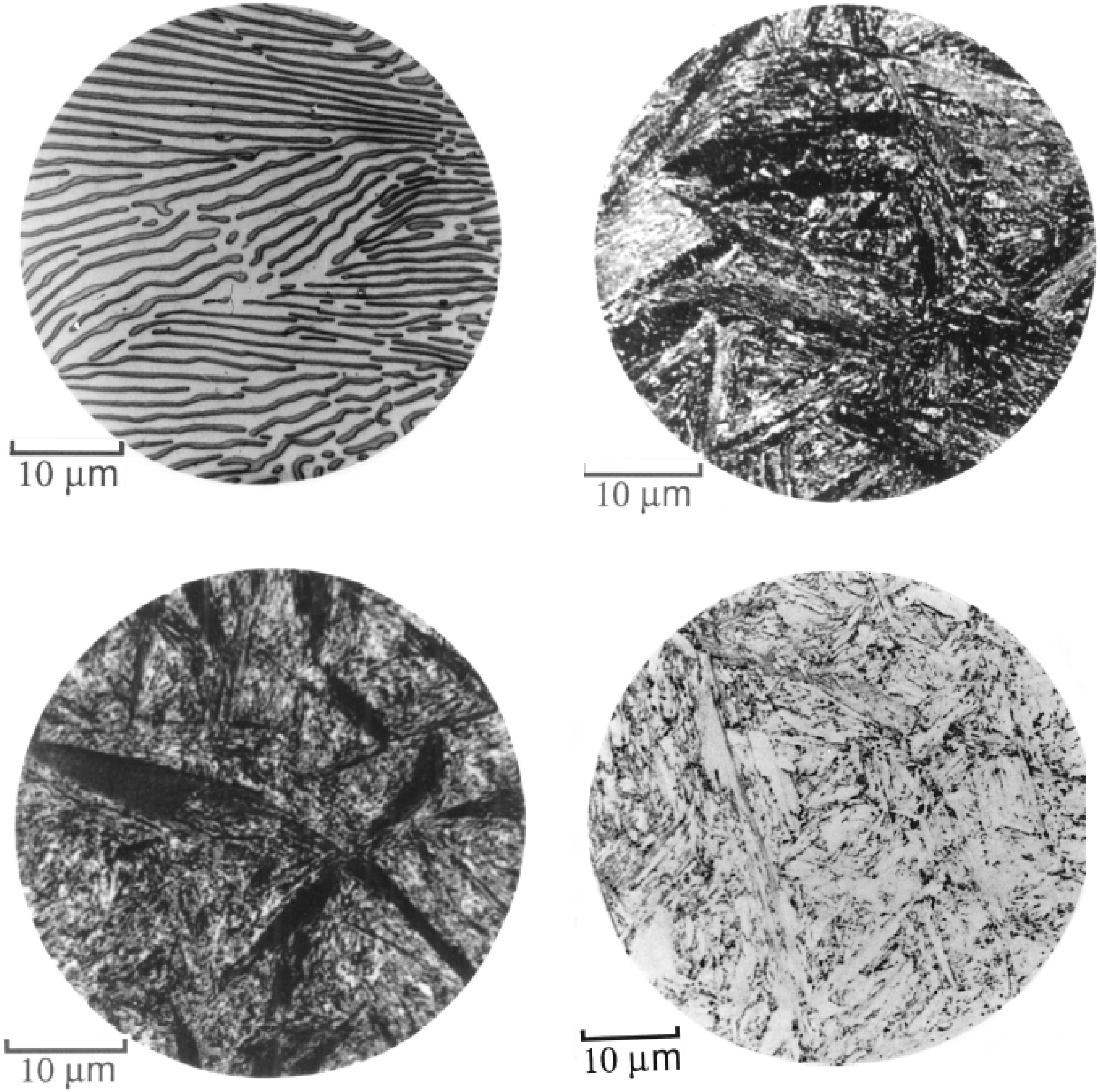


Fig. 1.1 Microstructures in a eutectoid steel: (a) Pearlite formed at 720 °C; (b) bainite obtained by isothermal transformation at 290 °C; (c) bainite obtained by isothermal transformation at 180 °C; (d) martensite. The micrographs were taken by Vilella and were published in the book *The Alloying Elements in Steel* (Bain, 1939). Notice how the bainite etches much darker than martensite, because its microstructure contains many fine carbides.

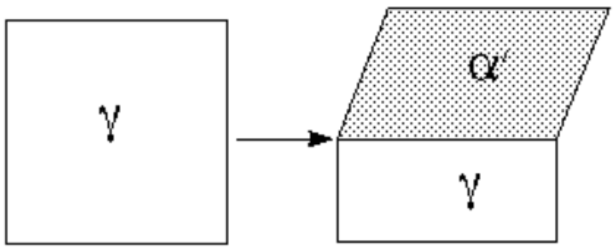
Martensitic transformations are diffisionless.

Martensite can form at very low temperatures, where diffusion, even of interstitial atoms, is not conceivable over the time period of the experiment. A low transformation temperature is not sufficient evidence for diffusionless transformation.

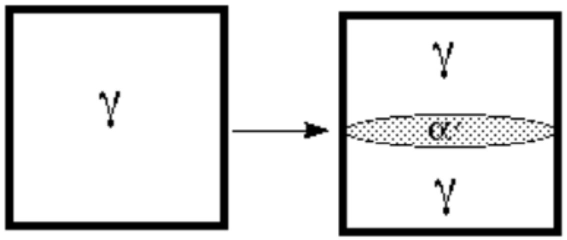
Martensite plates can grow at speeds which approach that of sound in the metal. In steel, this can be as high as 1100m/s, which compares with the fastest recorded solidifcation front velocity of about 80m/s in pure nickel. Such large speeds are inconsistent with diffusion during transformation.

The Habit Plane

This is the interface plane between austenite and martensite as measured on a macroscopic scale. For unconstrained transformations this interface plane is flat, but strain energy minimization introduces some curvature when the transformation is constrained by its surroundings. Nevertheless, the macroscopic habit plane is identical for both cases. Steels of vastly different chemical composition can have martensite with the same habit plane, and indeed, other identical crystallographic characteristics.



unconstrained transformation



constrained transformation

Orientation Relationships

The formation of martensite involves the coordinated movement of atoms. It follows that the austenite and martensite lattices will be intimately related. All martensitic transformations therefore lead to a reproducible orientation relationship between the parent and product lattices. It is frequently the case that a pair of corresponding close-packed planes in the ferrite and austenite are parallel or nearly parallel, and it is usually the case that corresponding directions within these planes are roughly parallel :

$$\begin{array}{l} \{1\ 1\ 1\}_\gamma \parallel \{0\ 1\ 1\}_\alpha \\ <1\ 0\ \bar{1}>_\gamma \parallel\ <1\ 1\ \bar{1}>_\alpha \end{array} \qquad \text{Kurdjumov–Sachs}$$

$$\begin{array}{l} \{1\ 1\ 1\}_\gamma \parallel \{0\ 1\ 1\}_\alpha \\ <1\ 0\ \bar{1}>_\gamma \quad \text{about } 5.3^\circ \text{ from} <1\ 1\ \bar{1}>_\alpha \text{ towards } <\bar{1}\ 1\ \bar{1}>_\alpha \end{array} \qquad \text{Nishiyama–Wasserman}$$

$$\begin{array}{l} \{1\ 1\ 1\}_\gamma \quad \text{about } 0.2^\circ \text{ from} \{0\ 1\ 1\}_\alpha \\ <1\ 0\ \bar{1}>_\gamma \quad \text{about } 2.7^\circ \text{ from} <1\ 1\ \bar{1}>_\alpha \text{ towards } <\bar{1}\ 1\ \bar{1}>_\alpha \end{array} \qquad \text{Greninger–Troiano}$$

KS Variant

24 KS orientations

Variant No.	Plane parallel (γ) // (α)	Direction parallel [γ] // [α]	Variant No.	Plane Parallel (γ) // (α)	Direction Parallel [γ] // [α]
1	(111) // (011)	[-110] // [11-1]	**13**	(1-11) // (011)	[110] // [11-1]
2	(111) // (011)	[-110] // [-11-1]	**14**	(1-11) // (011)	[110] // [-11-1]
3	(111) // (011)	[01-1] // [-11-1]	**15**	(1-11) // (011)	[10-1] // [-11-1]
4	(111) // (011)	[01-1] // [11-1]	**16**	(1-11) // (011)	[10-1] // [11-1]
5	(111) // (011)	[10-1] // [11-1]	**17**	(1-11) // (011)	[0-1-1] // [11-1]
6	(111) // (011)	[10-1] // [-11-1]	**18**	(1-11) // (011)	[0-1-1] // [-11-1]
7	(-111) // (011)	[110] // [11-1]	**19**	(11-1) // (011)	[-10-1] // [11-1]
8	(-111) // (011)	[110] // [-11-1]	**20**	(11-1) // (011)	[-10-1] // [-11-1]
9	(-111) // (011)	[01-1] // [-11-1]	**21**	(11-1) // (011)	[011] // [-11-1]
10	(-111) // (011)	[01-1] // [11-1]	**22**	(11-1) // (011)	[011] // [11-1]
11	(-111) // (011)	[-10-1] // [11-1]	**23**	(11-1) // (011)	[1-10] // [11-1]
12	(-111) // (011)	[-10-1] // [-11-1]	**24**	(11-1) // (011)	[1-10] // [-11-1]

Athermal Nature of Transformation

In the vast majority of cases, the extent of reaction is found to be virtually independent of time. At temperatures below the Ms temperature, it is known that the athermal martensitic transformation during cooling can be well described as the Koistinen and Marburger's empirical equation.

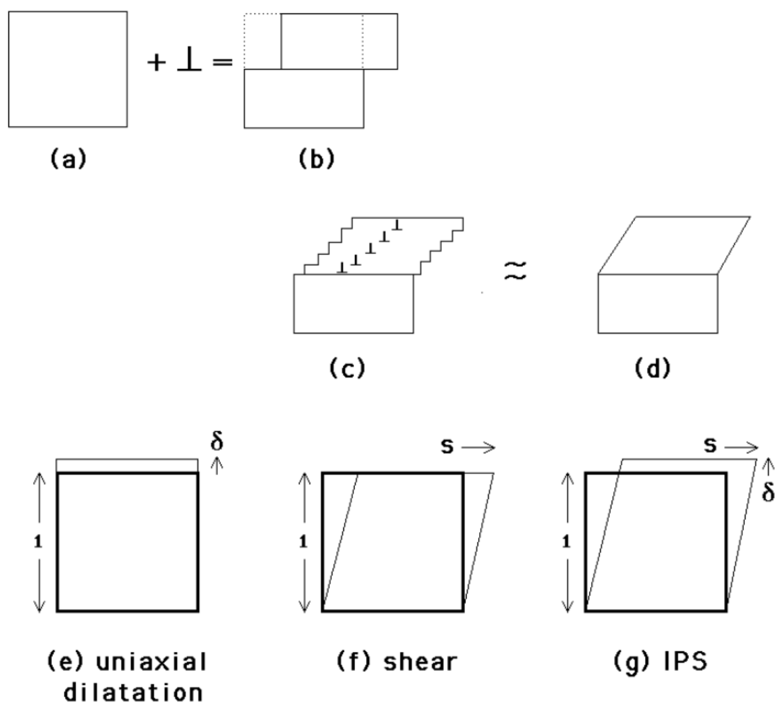
$$f = 1 - \exp[-0.011(M_s - T)]$$

Notice that time does not feature in this relation, so that the fraction of martensite depends only on the undercooling below the martensite-start temperature. This athermal character is a consequence of very rapid nucleation and growth.

Isothermal martensite is possible when nucleation is hindered.

Invariant Plane Strain

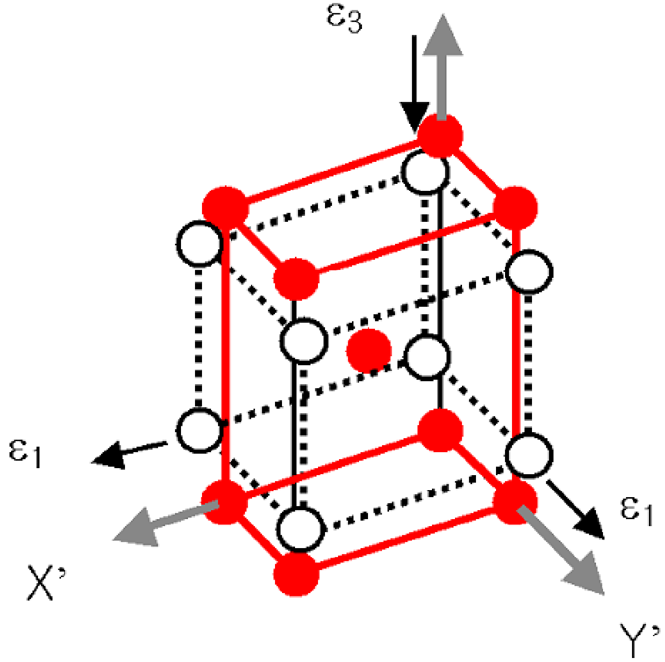
Since the martensitic tranformation proceeds through a cooperative motion of atoms, the interface between the parent and product crystals must be highly coherent. During the transformation, therefore, an undistorted and unrotated plane is needed. The deformation related with the shape change is called the invariant plane strain.



Bain Deformation

We now consider the nature of the deformation necessary to transform the FCC lattice of austenite into the BCC lattice of martensite. Such a strain was proposed by Bain in 1924 and hence is known as the 'Bain Deformation'.

$$\mathbf{fBf} = \begin{bmatrix} \eta_1 & 0 & 0 \\ 0 & \eta_1 & 0 \\ 0 & 0 & \eta_3 \end{bmatrix}$$

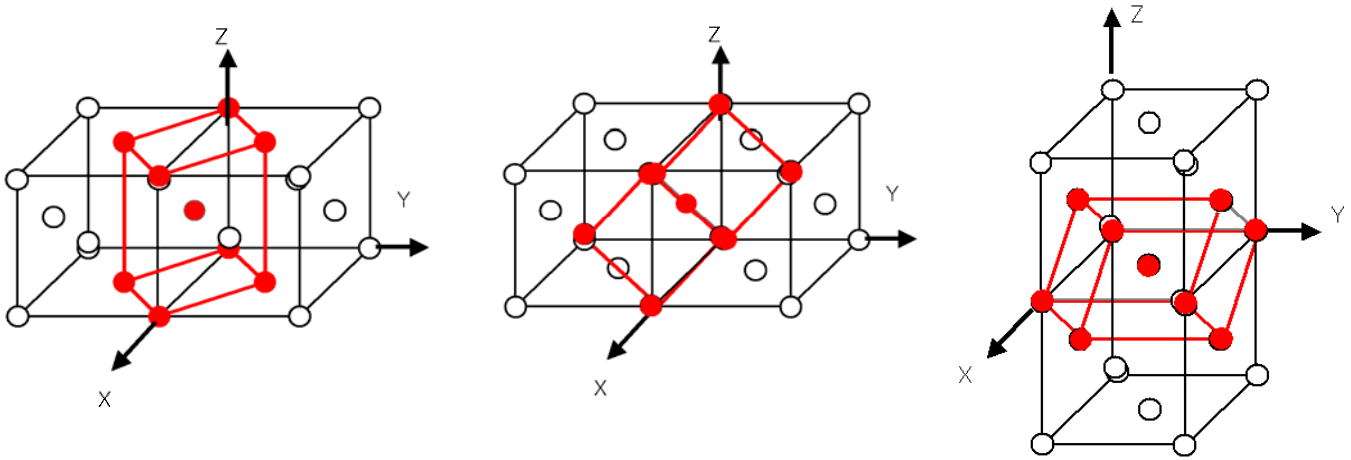


Bain Deformation

η1 and η3 can be calculated from the lattice parameter of FCC and BCC as follows ;

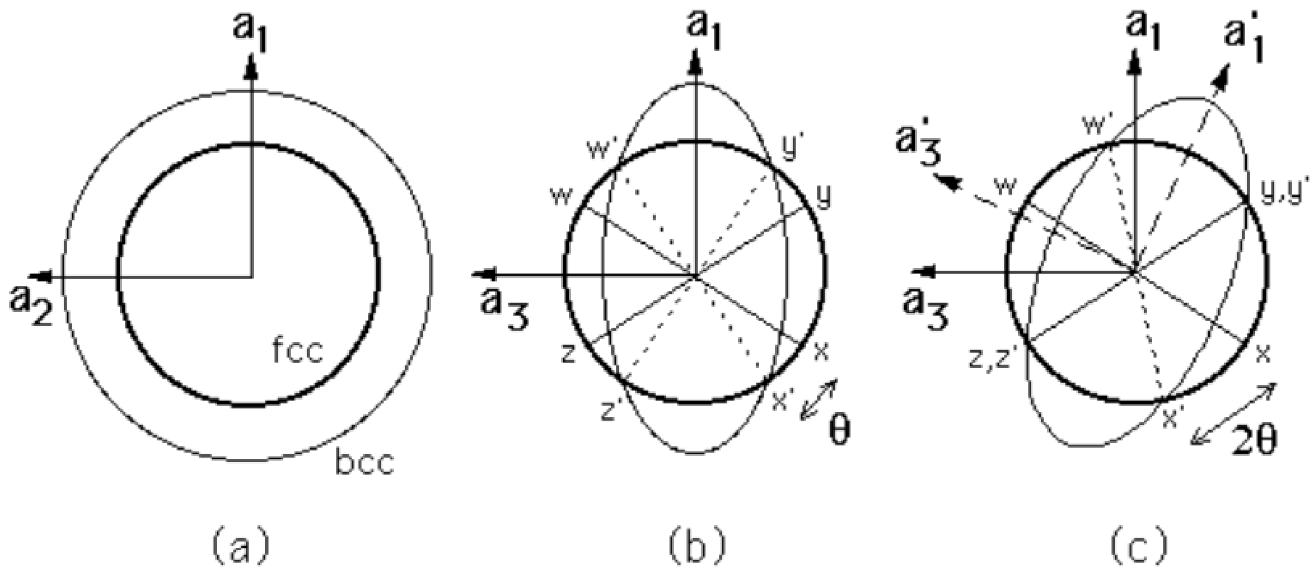
$$\eta_3 = \frac{a_{BCC}}{a_{FCC}} \qquad \eta_1 = \frac{\sqrt{2}\, a_{BCC}}{a_{FCC}} = \sqrt{2}\,\eta_3$$

Three variants of Bain deformation have one compressive axis and two tensile axes for the martensitic transformation.



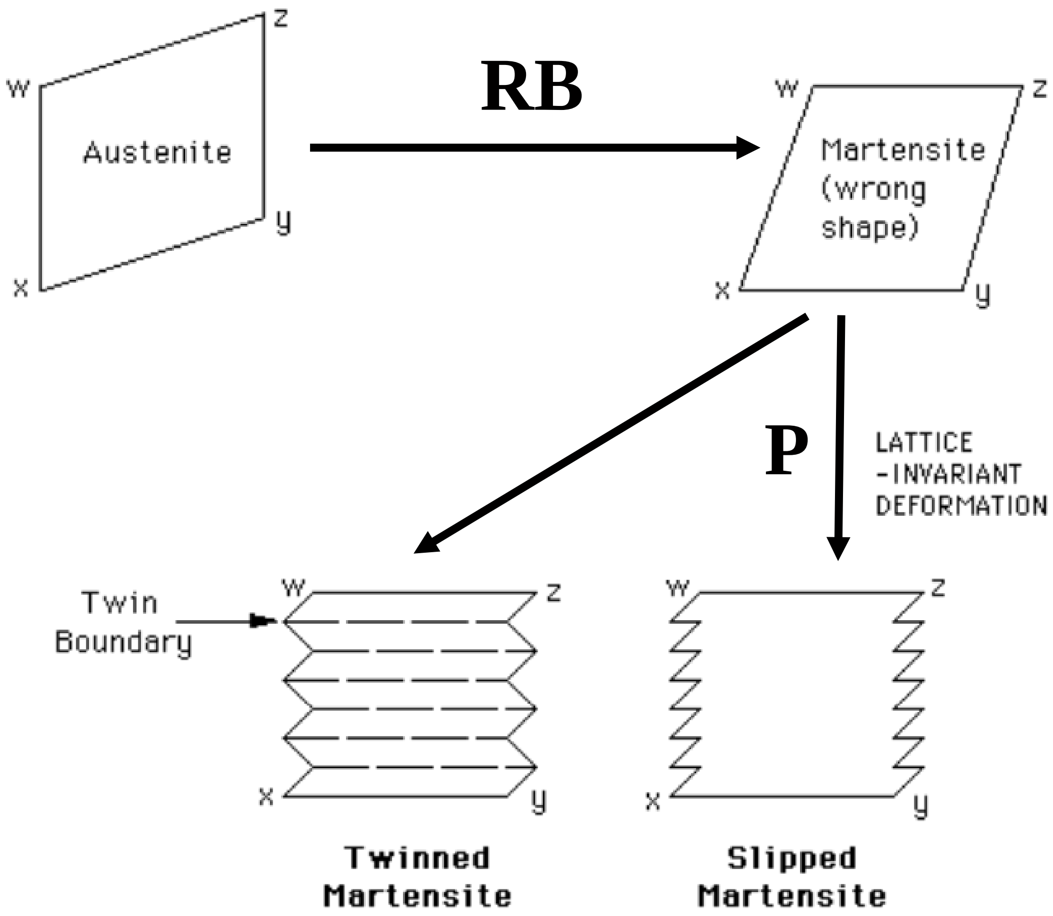
Bain Deformation (○FCC (γ) → ●BCC (α))

Deformations of Martensite Transformation



(a) and (b) show the effect of the Bain deformation on austenite, which when undeformed is represented as a sphere of diameter wx = yz in three-dimensions. The deformation transforms it to an ellipsoid of revolution. (c) shows the invariant-line deformation obtained by combining the Bain deformation with a rigid body rotation through an angle θ.

Deformations of Martensite Transformation



Correct macroscopic shape, correct structure

Phenomenological Theory of Martensite Transformation

Wechsler-Lieberman-Read theory

The total shape deformation :

$$\mathbf{P_1} = \mathbf{RBP}$$

The shape deformation associated with the displacive transformation without rigid body rotation can be expressed as follows **:**

$$\mathbf{F} = \mathbf{BP}$$

Phenomenological Theory of Martensite Transformation

Finally, we can get the Lagrangian transformation strain of each variant on the reference coordinate of BCC as follows :

$$\varepsilon_{ij}^{C} = \frac{1}{2}[(\mathbf{bFb})^{T}(\mathbf{bFb}) - \mathbf{I}]$$

$$\varepsilon_{ij}^{S} = a_{ik} \cdot a_{jl} \cdot \varepsilon_{kl}^{C}$$

where a_{ij} is the direction cosine which links the BCC crystal coordinate to the specimen coordinate.

The rotation matrix R can be expressed by :

$$\boldsymbol{R} = \begin{bmatrix} u_1{}^2(1-\cos\theta)+\cos\theta & u_1u_2(1-\cos\theta)-u_3\sin\theta & u_1u_3(1-\cos\theta)+u_2\sin\theta \\ u_2u_1(1-\cos\theta)+u_3\sin\theta & u_2{}^2(1-\cos\theta)+\cos\theta & u_2u_3(1-\cos\theta)-u_1\sin\theta \\ u_3u_1(1-\cos\theta)-u_2\sin\theta & u_3u_2(1-\cos\theta)+u_1\sin\theta & u_3{}^2(1-\cos\theta)+\cos\theta \end{bmatrix}$$

Phenomenological Theory of Martensite Transformation

For example of Fe-31Ni system :

$$\boldsymbol{d}_2 = \frac{1}{\sqrt{2}}[\bar{1}01], \qquad \boldsymbol{p}_2 = \frac{1}{\sqrt{2}}[10\bar{1}], \qquad \boldsymbol{t} = [010],$$

$$(\mathrm{gFg}) = \begin{bmatrix} 0.966338 & 0.082352 & 0 \\ -0.165798 & 0.923763 & 0 \\ 0 & 0 & 1.132136 \end{bmatrix}.$$

$$(\mathrm{fFf}) = \begin{bmatrix} 0.986773 & 0 & -0.145363 \\ 0 & 1.132136 & 0 \\ 0.102788 & 0 & 0.903327 \end{bmatrix}$$

$$\boldsymbol{R} = \begin{bmatrix} 0.991185 & -0.032641 & 0.128398 \\ 0.018684 & 0.993927 & 0.108438 \\ -0.131157 & -0.105083 & 0.985776 \end{bmatrix}$$