

## 15 *The Transformations in Steel*

Probably the most interesting revelations are made when *all* of the decomposition reactions of austenite are examined together. And the most awkward question seeks to discover the difference between the variety of transformation products. This chapter is intended to be a brief picture of how these transformations fit together, in a way which is consistent with the available experimental and theoretical data (Fig. 15.1).

There is ample evidence that the different forms of ferrite can be categorised into those which grow by displacive transformation and the others which grow by a reconstructive mechanism. Amongst the displacive transformations are Widmanstätten ferrite, bainite, acicular ferrite and martensite, all of which are characterised uniquely by their plate or lath shapes and the striking invariant-plane strain surface relief which accompanies transformation. An important feature of this strain is the large shear component which is the dominant reason for the plate shape of the transformation product. There is no equilibrium at the transformation front; substitutional solutes do not partition between the parent and product phases.

Widmanstätten ferrite grows at high temperatures by a paraequilibrium mechanism in which the plates lengthen at a rate controlled by the diffusion of carbon in austenite. This diffusion does not contradict its displacive character because interstitials can migrate without affecting the IPS shape deformation. The transformation occurs at small driving forces, so that the shape change consists of two adjacent invariant-plane strains which tend to mutually accommodate and hence reduce the strain energy. This also explains the thin-wedge shape of Widmanstätten ferrite because the adjacent plates are different crystallographic variants (Fig. 15.2).

Carbon must diffuse during the nucleation of both Widmanstätten ferrite and bainite. Nucleation probably occurs by a process akin to the dissociation of arrays of dislocations. This follows from the observation that the activation energy for nucleation is directly proportional to the driving force, rather than the inverse square relationship implied by a heterophase fluctuation model of nucleation. Both Widmanstätten ferrite and bainite develop from the same nucleus; it develops into bainite if diffusionless growth is possible at the temperature where nucleation becomes possible. Otherwise it evolves into Widmanstätten ferrite.

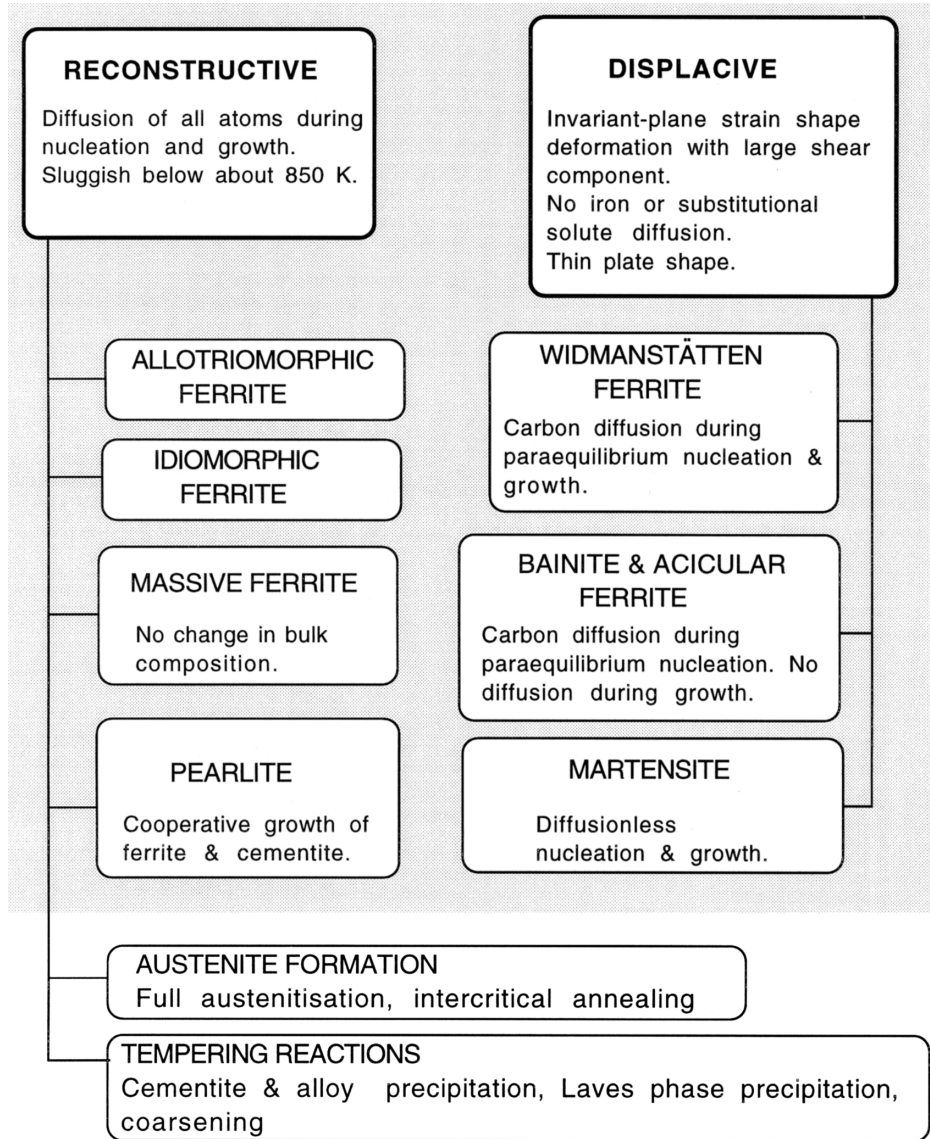
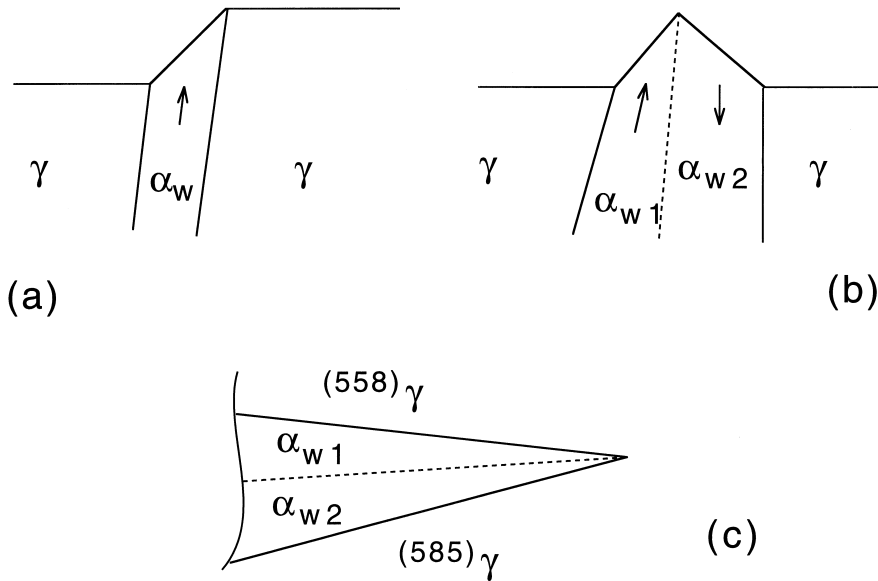


Fig. 15.1 Flowchart summarising the characteristics of transformations in steels.

Bainite probably grows without diffusion, but excess carbon is soon after transformation, rejected into the residual austenite. The partitioned carbon may then precipitate as carbides, giving the classical upper bainitic microstructure. At somewhat lower transformation temperatures where the



**Fig. 15.2** (a) A single invariant-plane strain shape deformation. (b) The combined effect of two mutually accommodating, back-to-back IPS deformations. (c) The morphology of two plates, with different habit plane variants, growing together in a mutually accommodating manner.

partitioning of carbon is slower, a proportion of the excess carbon has the opportunity to precipitate inside the bainitic ferrite. This leads to the lower bainitic microstructure.

Bainite grows at temperatures where the austenite is mechanically weak and unable to elastically accommodate the shape deformation. As a result, the dislocations generated during the plastic deformation of the adjacent austenite, cause a loss of coherency at the  $\alpha_b/\gamma$  interface. The growth of the bainite platelet therefore is arrested before it hits any hard obstacle such as an austenite grain boundary. Continued transformation therefore requires new platelets to form, giving rise to clusters of parallel sub-units with identical crystallographic orientation, habit plane and size. These clusters are known as sheaves of bainite. Acicular ferrite is an alternative, more chaotic morphology of bainite in which the plates are intragranularly nucleated on non-metallic inclusions and hence grow in many different directions from the nucleation site.

The possibility remains that the transition from Widmanstätten ferrite to bainite involves a gradual increase in carbon supersaturation, rather than a sudden change from paraequilibrium to diffusionless growth.

Martensitic transformation is diffusionless, both during nucleation and during growth.

The reconstructive transformations include allotriomorphic and idiomorphic ferrite, and pearlite in its various forms. It is important to appreciate that all elements, including iron, must diffuse during reconstructive transformation in order to achieve the structural change without the strains characteristic of displacive reactions. None of these transformations are associated with shear strains.

A prominent feature of the eutectoid decomposition reaction which leads to the formation of pearlite is that the ferrite and carbide phases grow with a common transformation front with the austenite. They are said to grow cooperatively.

Figure 15.1 lists the growth of austenite by a reconstructive mechanism. This is not always the case. However, extraordinarily large heating rates are needed in all practical circumstances to change the growth mode into one which is displacive. The precipitation of alloy carbides undoubtedly occurs by reconstructive transformation with the long-range diffusion of substitutional solutes. However, this is not necessarily the case for the iron carbides, which can grow at temperatures where the diffusion of iron is inconceivable.

## 15.1 Key Characteristics of Transformations in Steels

Table 15.1 lists the key characteristics of phase transformations in steels. The nomenclature used for the transformation products is as follows: martensite ( $\alpha'$ ), lower bainite ( $\alpha_{lb}$ ), upper bainite ( $\alpha_{ub}$ ), acicular ferrite ( $\alpha_a$ ), Widmanstätten ferrite ( $\alpha_w$ ), allotriomorphic ferrite ( $\alpha$ ), idiomorphic ferrite ( $\alpha_i$ ), pearlite ( $P$ ), substitutional alloying elements ( $X$ ). Consistency of a comment with the transformation concerned is indicated by (=), inconsistency by ( $\neq$ ); cases where the comment is only sometimes consistent with the transformation are indicated by a bullet ( $\bullet$ ). The term *parent*  $\gamma$  implies the  $\gamma$  grain in which the product phase grows. Note that it is not justified to distinguish massive ferrite from  $\alpha$ .

## 15.2 Notes Related to Table 15.1

Nucleation and growth reactions are of first order in the Ehrenfest classification; in all such reactions, the parent and product phases can coexist, and are separated by well-defined interfaces. Martensitic transformations, although they can be rapid, still involve a nucleation and growth process.

It is significant that all of the ferrite crystals which grow in the form of plates cause an invariant-plane shape deformation which is dominated by shear. The ferrite within pearlite does not have a plate morphology; Hillert showed some time ago that it is wrong to consider pearlite as alternating layers of ferrite and

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**Table 15.1** Characteristics of solid-state transformations in steels.

Comment	$\alpha'$	$\alpha_{lb}$	$\alpha_{ub}$	$\alpha_a$	$\alpha_w$	$\alpha$	$\alpha_i$	$P$
Nucleation and growth reaction	=	=	=	=	=	=	=	=
Plate shape	=	=	=	=	=	≠	≠	≠
IPS shape change with large shear	=	=	=	=	=	≠	≠	≠
Diffusionless nucleation	=	≠	≠	≠	≠	≠	≠	≠
Only carbon diffuses during nucleation	≠	=	=	=	=	≠	≠	≠
Reconstructive diffusion during nucleation	≠	≠	≠	≠	≠	=	=	=
Often nucleates intragranularly on defects	=	≠	≠	=	≠	≠	=	≠
Diffusionless growth	=	=	=	=	≠	≠	≠	≠
Reconstructive diffusion during growth	≠	≠	≠	≠	≠	=	=	=
Atomic correspondence (all atoms) during growth	=	=	=	=	≠	≠	≠	≠
Atomic correspondence only for atoms in substitutional sites	=	=	=	=	=	≠	≠	≠
Bulk redistribution of X atoms during growth	≠	≠	≠	≠	≠	⊗	⊗	⊗
Local equilibrium at interface during growth	≠	≠	≠	≠	≠	⊗	⊗	⊗
Local paraequilibrium at interface during growth	≠	≠	≠	≠	=	⊗	⊗	≠
Diffusion of carbon during transformation	≠	≠	≠	≠	=	=	=	=
Carbon diffusion-controlled growth	≠	≠	≠	≠	=	⊗	⊗	⊗
Co-operative growth of ferrite and cementite	≠	≠	≠	≠	≠	≠	≠	=
High dislocation density	=	=	=	=	⊗	≠	≠	≠
Incomplete reaction phenomenon	≠	=	=	=	≠	≠	≠	≠
Necessarily has a glissile interface	=	=	=	=	=	≠	≠	≠
Always has an orientation within the Bain region	=	=	=	=	=	≠	≠	≠
Grows across austenite grain boundaries	≠	≠	≠	≠	≠	=	=	=
High interface mobility at low temperatures	=	=	=	=	=	≠	≠	≠
Displacive transformation mechanism	=	=	=	=	=	≠	≠	≠
Reconstructive transformation mechanism	≠	≠	≠	≠	≠	=	=	=

cementite – instead a colony of pearlite is an interpenetrating bicrystal of ferrite and cementite.

Reconstructive diffusion is the flow of matter necessary to avoid the strains characteristic of displacive transformations. A diffusional transformation may phenomenologically be regarded as a combination of a lattice change and a recrystallisation of the product phase, reconstructive diffusion being the flow necessary for the recrystallisation process.

In diffusionless transformations, it is possible to specify (in a localised region at least) how particular vectors, planes and unit cells of one structure (defined by an imaginary labelling of the individual atoms) are derived from *corresponding* vectors, planes and unit cells of the other structure. This is

termed a lattice correspondence and it defines a pure lattice deformation which carries the original lattice points, or some fraction of these points into points of the new lattice. When interstitial atoms are present, they may move over large distances during transformation without affecting the lattice correspondence; this is sometimes loosely expressed by stating that there is an atomic correspondence for the solvent and substitutional solute atoms but not for the interstitial atoms. A further relaxation of the condition is to allow the solvent and substitutional solute atoms to be displaced during transformation among the sites specified by the lattice correspondence, but not to create new sites or to destroy any specified sites; in this way the lattice correspondence is preserved but there is no longer an atomic correspondence. Note that in the classification presented above, the single atomic jumps of interstitial atoms needed to destroy Zener ordering (which is produced automatically by the Bain correspondence) are not taken into account.

Even though two crystals may have an identical *bulk* composition, it may not be concluded that their compositions at the transformation interface are identical. There are modes of transformation (e.g. negligible partitioning local equilibrium) where the bulk compositions are predicted to be identical but where the phases differ in the vicinity of the transformation interface. For plain carbon steels, there is no difference between equilibrium and paraequilibrium.

The incomplete reaction phenomenon implies that when a reaction can be studied in isolation, it stops before the phases reach their equilibrium or paraequilibrium compositions when stored energy terms have been accounted for.

An orientation within the Bain region means a reproducible relation which may be irrational but is close to the rational NW or KS relations.

Massive ferrite is not classified as a separate morphology since it can be included within allotriomorphic or idiomorphic ferrite.