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# The microstructure of dislocated martensitic steel: Theory

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**Abstract**

Recent experimental studies of the microstructure of dislocated martensite in low-carbon steel have shown that its superficially complex microstructure is, in fact, a simple hierarchical pattern whose basic element is a composite block containing two Kurdjumov–Sachs variants of the $\alpha'$ phase that share the same Bain axis. The blocks are plates with interfaces generally parallel to $\{011\}_\alpha$ planes that can be stacked into four crystallographically distinguishable packets. When the prior austenite grain contains all four packets its transformation can be a simple dilatation that involves no net shear. In the present paper we use the crystallographic theory of dislocated martensite to show that the stackable composite martensite plate is the simplest transformed plate that can be constructed that preserves a close-packed plane ($\{011\}_\alpha \| \{111\}_\gamma$) and has an invariant $\{111\}_\gamma$ habit plane, as the experimental results require. The 12 distinct variants of this plate can be configured into a microstructure that duplicates the patterns and pole figures found experimentally. The results suggest that there is no single-variant martensite plate that can be stacked in this way without substantial strain, though the theory does predict the single-variant plates with $\{557\}_\alpha$ habit planes and Greninger–Troiano orientation relations that are found in alloys with large fractions of retained austenite.

*Keywords:* Martensite; Dislocated martensite; Low-carbon steel; Microstructure

## 1. Introduction

As discussed in the companion paper [1], which specifically addresses the microstructure of 9Ni steel, the excellent mechanical properties of dislocated martensitic steels depend on the ability of the transformation to complete the conversion of a polygranular body of austenite without introducing severe internal stresses. Given the significant distortion required to generate the body-centered cubic (bcc, $\alpha'$) structure from face-centered cubic (fcc, $\gamma$) through a spontaneous shear (the "Bain strain" illustrated in Fig. 1), it is superficially difficult to accomplish this. To succeed, the transformation must include three salient features: an invariant plane to initiate the transformation; a method of stacking crystallographic variants of the $\alpha'$ to accommodate shear and continue the transformation; and a microstructural pattern that is capable of transforming prior $\gamma$ grains without significantly changing their shape.

The microstructure of 9Ni steel appears to incorporate all of these features in a hierarchical configuration that, while very complex in appearance, is surprisingly simple [1]. The $\alpha'$ phase that is created in the martensitic transformation has a Kurdjumov–Sachs (KS) crystallographic relation to the parent austenite, with a total of 24 crystallographically distinct $\alpha'$ variants. These divide into four sets, each set containing the six variants whose close-packed planes ($\{011\}_\alpha$) parallel a particular one of the four close-packed planes of the $\gamma$-phase ($\{111\}_\gamma$ (Fig. 2). The basic element of the microstructure is the composite block, a platelet that combines the two KS variants from a given set that share the same Bain axis (the axis of compression in the Bain strain that transforms $\gamma$ to $\alpha'$). The blocks are plates with surfaces generally parallel to

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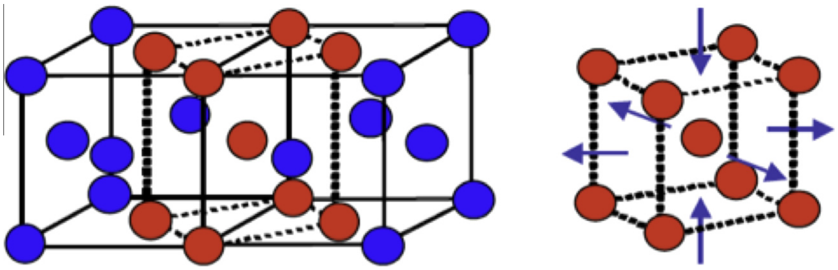

Fig. 1. The Bain transformation from fcc to bcc. The body-centered tetragonal cell outlined in red is compressed along $[0\,0\,1]_\gamma \| [0\,0\,1]_\alpha$ and expanded in the basal plane to achieve the bcc structure.

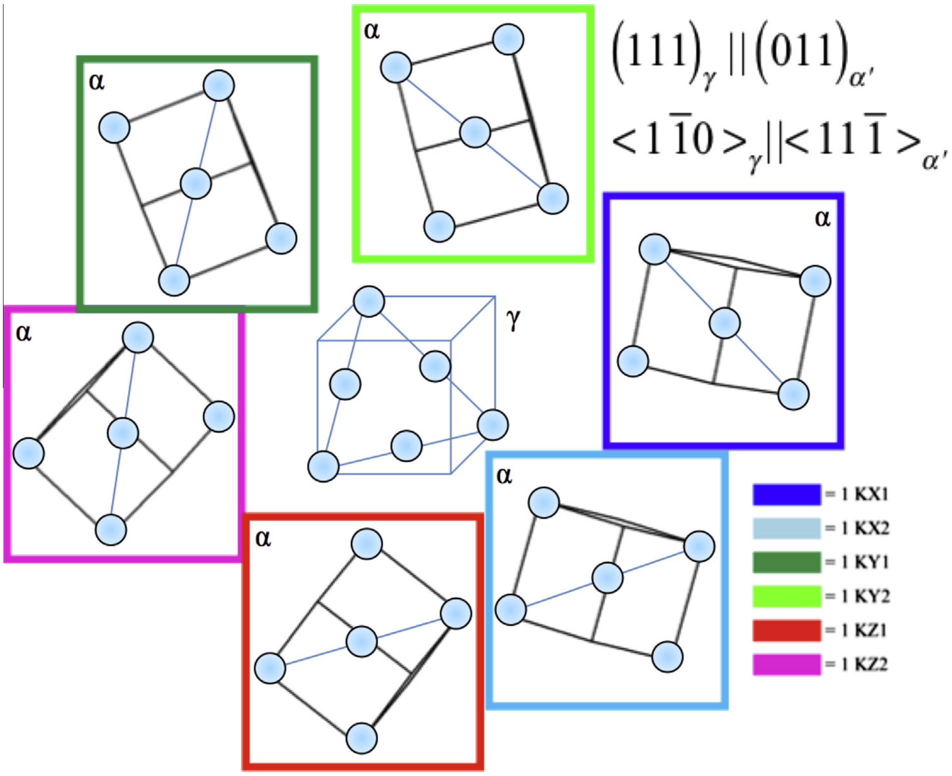

Fig. 2. The six crystallographic variants of bcc that satisfy the KS relation on $(1\,1\,1)_\gamma$. The variants are identified at lower right with the notation used in Ref. [1]. Variants of the same color (red, blue, green) have the same Bain axis. Variants that share the same close-packed direction are twinned with respect to one another. Variants colored dark (light) are rotated 120° from one another in the plane. Since there are four choices for the $\{1\,1\,1\}_\gamma$ plane, there are 24 KS variants. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

close-packed $\{0\,1\,1\}_\alpha$ planes (Fig. 3). It follows that the three distinct blocks that share a $\{0\,1\,1\}_\alpha$ (or, equivalently, $\{1\,1\,1\}_\gamma$) plane can be stacked to form a packet. The four distinct packets then fill the prior austenite grain. The complete microstructure uses all 24 KS variants; if these appear with equal volume fractions, then the net transformation strain is a pure dilatation, changing the volumes of the parent grains without changing their shapes and, hence, producing no net shear stress.

A very similar pattern has been observed in other low-carbon martensites [2–5], suggesting that this microstructure is typical for dislocated martensite in low-carbon steels, and is responsible for their excellent mechanical properties.

Given the pattern in which the composite blocks of dislocated martensite stack to make packets that fill space, it seems very likely that the close-packed planes, $\{0\,1\,1\}_\alpha \| \{1\,1\,1\}_\gamma$, are invariant planes for the martensitic transformation, and the stacking of the three distinct blocks into a packet largely eliminates the transformation shear. Moreover, given the ubiquity of the composite, Bain-variant block, it is also seems very likely that no simpler shear-free structure exists, i.e. that there is no single-variant plate that has an invariant plane that permits a stacking that fills space without internal shear. However, to our knowledge, this result has not been established, and no theoretical basis has been given for the self-accommodating, space-filling configuration of distinct crystallographic variants of dislocated martensite that occurs in low-carbon steel.

In the present paper we use the crystallographic theory of dislocated martensite developed by one of us some years