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The microstructure of lath martensite in quenched 9Ni steel

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Abstract

Many of the most useful structural steels have dislocated lath martensitic structures. The microstructures of these steels are complex since each prior austenite grain contains as many as 24 different crystallographic variants of the γ(fcc)–α'(bcc) transformation. Recent research, using electron backscatter diffraction (EBSD), has significantly clarified the "block-and-packet" structure of lath martensite in low-carbon steel. The blocks are bivariant composites of two transformation variants, with the three distinct blocks stacked so that all six of the possible variants of the packet are used. The present work was undertaken to complete the description of this structure and identify its underlying causes. We address these issues in two steps. First, we present an EBSD characterization of lath martensite in low-carbon 9Ni steel. The results show that all packets have the bivariant block structure, and, with the proper notation, the full hierarchical structure has a simple pattern that is easily described and visualized. The results are readily explained on the basis of two assumptions: (i) the bivariant block, in contrast to a single-variant block, has an α'–γ invariant plane very near $\{011\}_{\alpha''}\|\{111\}_{\gamma}$, which permits the plate-shaped blocks to stack without significant strain to form a packet; (ii) the transformation goes to completion, with the consequence that the net strain in the prior austenite grain is a simple dilatation, and polygranular bodies can transform martensitically without significant residual stress. In a companion paper we use an appropriate modification of the crystallographic theory of lath martensite to validate the first of these assumptions.

Keywords: Martensite; Lath martensite; Dislocated martensite; 9Ni steel; Microstructure of steel

1. Introduction

1.1. The microstructure of lath martensite in low-carbon steel

Most of the preferred high-strength structural steels are martensitic steels. The spontaneous structural transformation from face-centered cubic (fcc) to body-centered cubic (bcc) involves a substantial strain that is accommodated by introducing a high density of defects. When the carbon content is high (>~0.6 wt.% in Fe–C steels), or the martensitic transformation temperature is low, the primary defects are internal twins. The resulting "twinned" martensite may be very strong, but is, ordinarily, too brittle for structural use. When the carbon content is relatively low (<0.6 wt.%) and the alloy content is suitable the defects are dislocations, and the resulting "dislocated" or "lath" martensite often has a very useful combination of strength and toughness [1].

While its mechanical properties may be attractive, the microstructure of dislocated lath martensite is superficially complex (Fig. 1) and has proven difficult to characterize or describe in any simple way. The reasons for the complex microstructure are fundamental. The preferred crystallographic relations between the parent austenite and the martensite product allow many crystallographic variants (24 in the case of the common Kurdjumov–Sachs (KS) relation), and most or all of these appear during the transformation of each prior austenite grain. The resulting entanglement of

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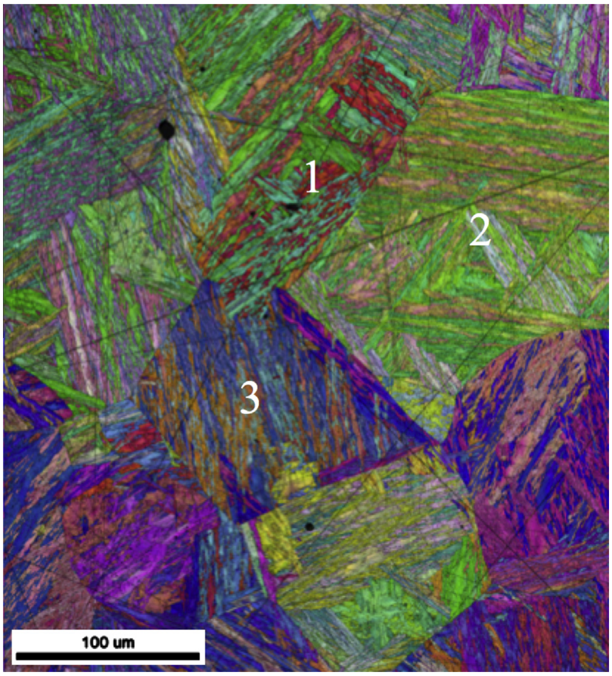

Fig. 1. EBSD map of the dislocated martensitic structure of 9Ni steel, as quenched. Three prior austenite grains are labeled.

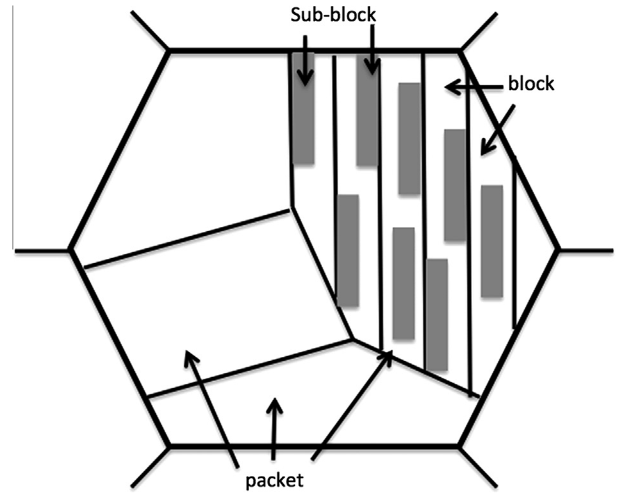

Fig. 2. Schematic cross-section of the block and packet structure of dislocated martensite in a prior austenite grain. The bivariant block structure is shown for one packet only.

multiple variants produces a microstructure that is, at least superficially, a very complicated one.

The characterization of the microstructure of even the simplest martensitic steel requires its description at three hierarchical levels: the elementary crystallites ("laths") of the martensitic phase; the local assembly of the laths into "blocks" and "packets"; and the arrangement of these microstructural elements into the patterns that fill prior austenite grains [2,3]. The properties of the steel are influenced by microstructural details at each level of this hierarchy.

Recent research using electron backscatter diffraction (EBSD) techniques to characterize the microstructure of lath martensite on the intermediate (mesoscopic) scale has produced a number of important observations that have significantly advanced the understanding of this structure [4–9]. This work has concentrated on the structure of packets of lath martensite in low-carbon steels, and has revealed a structure like that shown schematically in Fig. 2. The laths within a packet have a crystallographic relation to the parent austenite that is on or close to the KS relation:

$$(0\,1\,1)_{\alpha'}||(1\,1\,1)_{\gamma} \quad \langle 1\,1\,1\rangle_{\alpha'}||\langle 1\,1\,0\rangle_{\gamma} \tag{1}$$

where $(0\,1\,1)_{\alpha'}$ is the common close-packed plane of the laths in the packet, parallel to a particular $(1\,1\,1)_{\gamma}$ plane of the parent austenite, and the six close-packed $\langle 1\,1\,1\rangle_{\alpha'}$ directions in the $(0\,1\,1)_{\alpha'}$ plane are parallel (or almost so) to the corresponding close-packed directions in $(1\,1\,1)_{\gamma}$. There are, hence, six KS variants within the packet (Fig. 3). These are used to form three crystallographically distinct planar blocks. Each block is a bivariant composite plate of two particular KS variants. In the original work the two variants were identified as the pairs with low-angle boundaries. More recently it has been recognized that the paired variants are the two that have the same Bain axis (the compression axis in the Bain strain that creates α' from γ) [10,11]. The interblock boundaries in the packet are approximately planar, and are roughly parallel to the $(0\,1\,1)_{\alpha'}$ plane of the packet [8].

The packet structure outlined here has been found in a number of low-carbon martensites, including Fe–C [4], Fe–Mn–C [5], Fe–Ni–Co maraging steel [5] and 9Ni steel [6], and appears to be the common structure of lath martensite in low-carbon steel. However, there are indications that this packet structure is not so well-developed in lath martensite with higher carbon contents.

In fact, there are clear indications of this bivariant block structure in transmission electron microscopy (TEM) studies of low-carbon steels performed long before EBSD techniques became available. A particularly clear example appears in the 1974 study of Fe–0.2C by Apple, Caron and Krauss [1,12]. They show TEM micrographs of martensite plates that include irregularly shaped volumes of two distinct variants, differentiated by the distinct $\{5\,5\,7\}_{\gamma}$ habits of the laths.

1.2. Outstanding issues

The revelation of the packet structure illustrated in Fig. 2 is an important clarification of the superficially complex microstructure of lath martensitic steel. However, there are a number of issues that remain, including the underlying causes for this interesting microstructural pattern, We address these issues experimentally in the following, using the particular example of 9Ni steel, and in the accompanying theoretical paper [13]. The specific questions we shall address include the following.