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Anisotropy of strength and plasticity in lath martensite steel

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ABSTRACT

Microtensile testing with a crystal plasticity analysis was employed using single block structured specimens to elucidate the anisotropic plasticity of lath martensite steel. Habit-plane-orientation-dependent yielding occurred in the single block specimens, as well as in the single packet specimens. This indicated that the plastic anisotropy arose from the substructure included in the block. The crystal plasticity analysis successfully reproduced the stress-strain behaviour of the single block and single packet structures by considering the dependency of the slip activity on the habit plane orientation. These calculations revealed that the restriction of the slip transfer at the block and sub-block boundaries slightly increased the flow stress, while the austenite retaining between the martensite laths might impact the slip activity, leading to the anisotropy of the strength and plasticity.

1. Introduction

As a result of increasing crash safety and fuel economy performance requirements, there is a demand for high-strength steels with higher capabilities in the automobile industry [1,2]. Among these high-strength steels, dual-phase steel and transformation-induced plasticity steel have attracted much attention because of their excellent balance between strength and ductility [3,4]. In these steels, the distribution and morphology of the martensitic phase and the tendency towards martensitic transformation impact the mechanical properties [5–8]. Therefore, in high-strength steels, it is important to mechanistically understand the effect of the martensite on the mechanical characteristics.

In low-to-medium carbon steels, the martensite microstructure is composed of a hierarchical structure that includes the prior austenite grains, packets, blocks, and laths, as schematically shown in Fig. 1 [9]. The martensite laths are formed based on the Kurdjumov-Sachs (K-S) orientation relationship from austenite. There are twenty-four martensite variants originating from a single austenite grain. The packet is characterised by an aggregation of blocks with a common {111} habit plane from the prior austenite grain. Thus, the packet can contain six martensite variants. Recent progress in microstructural characterisation techniques such as electron back-scatter diffraction (EBSD) analysis, transmission electron microscopy, and three-dimensional tomography has helped clarify the details of the martensite microstructure [9–12]. An EBSD study by Stormvinter et al. [10] revealed that the carbon content has a strong impact on the variant pairing tendency of martensite. With a low carbon content, variant pairing occurs within a close-packed group that consists of six variants with a common habit plane, and its tendency decreases with increasing carbon content [10]. It was found [9] that the packet was composed of three parallel blocks with different crystallographic orientations, and each block consisted of a pair of variants with a specific K-S orientation relationship, i.e. sub-block (Fig. 1). In addition, a three-dimensional atom probe study by Morito et al. revealed [11] that the austenite films were retained between the martensite laths and contained high carbon when compared to the martensite laths. Although the lath martensite has a complicated microstructure, the microconstituents have defined crystallographic orientation relationships, as previously mentioned. Therefore, it is necessary to analyse the deformation behaviour from a crystallographic perspective to elucidate the strengthening of the lath martensite.

Recent advances in nano/micro-mechanical testing techniques such as nanoindentation [13,14], microbending [15], microcompression [16], and microtensile testing [17,18] have made it possible to evaluate the mechanical characteristics of the microconstituents in martensite structures. Microtensile tests of single packet structures revealed a habit-plane-orientation-dependent yielding, suggesting that a block boundary effectively acts as a barrier to the motion of dislocations [17]. A compression study using micropillars with block and packet boundaries revealed significant strain hardening due to the geometric constraint by both the boundaries [16]. A microbending study indicated that a block boundary restricts the dislocation motion, while a sub-block boundary does not significantly impact the strengthening [15]. In contrast, a uniaxial microtensile study by Du et al. [18] revealed

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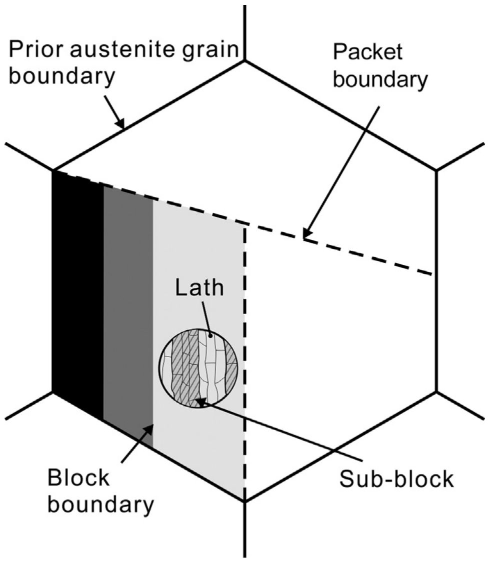

Fig. 1. Schematic illustration showing hierarchical structure of lath martensite steel (after Morito et al. [9]).

that both block and sub-block boundaries act as barriers to the dislocation motion, while the contribution of the sub-block to the strengthening is slightly lower than that of the block boundary. Therefore, the role of each boundary in the plasticity of the lath martensite structure is controversial.

Table 1
Dimensions (μm) of microtensile specimens used in this study. *L*, *W*, *T*, and *R* show the length, width, and thickness of the gauge section, and the radius of the curves in the specimen shoulders, respectively.

	L	*W*	*T*	*R*
SB1	35.0	13.5	16.0	7.0
SB2	40.0	14.7	16.8	8.0
SB3	25.0	11.4	11.1	5.0

Simulations by Maresca et al. [19–21] have recently indicated that localised shearing along the lath habit plane dominates the plasticity of the lath martensite structure. Microtensile tests of single block structures were performed in the present study with special focus on the crystallographic orientation. A crystal plasticity analysis was employed to identify the slip activity in the microtensile specimens.

2. Material and experimental methods

The material used in the present study was a low-carbon, low-

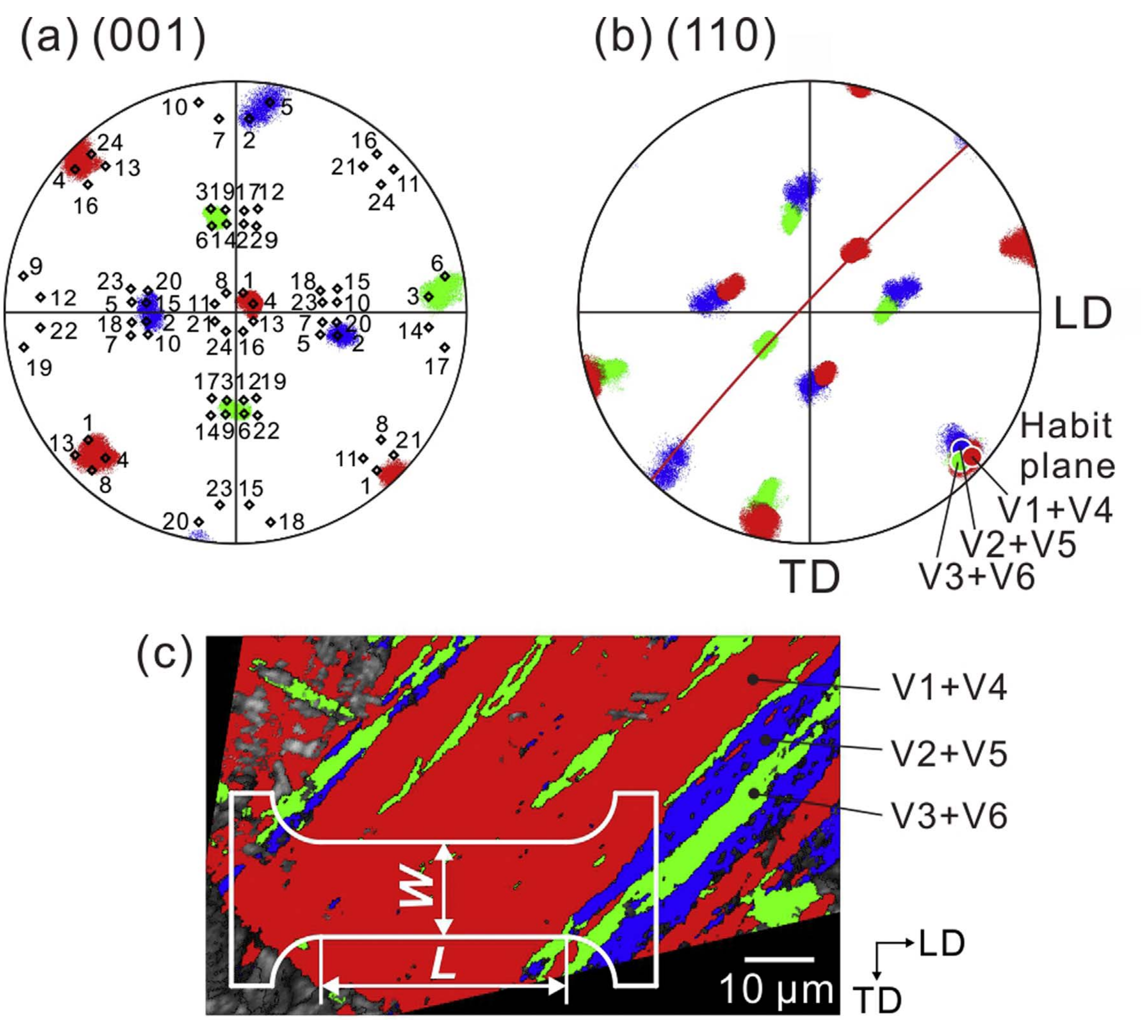

Fig. 2. (a and b) (001) and (110) pole figures of martensite and (c) corresponding colour-coded map overlaid by schematic illustration of tensile specimen. The length (*L*), width (*W*), and thickness (*T*) of the microtensile specimens are listed in Table 1. LD and TD denote the loading and transverse directions, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).