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A correlative approach to segmenting phases and ferrite morphologies in transformation-induced plasticity steel using electron back-scattering diffraction and energy dispersive X-ray spectroscopy

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ABSTRACT

Using a combination of electron back-scattering diffraction and energy dispersive X-ray spectroscopy data, a segmentation procedure was developed to comprehensively distinguish austenite, martensite, polygonal ferrite, ferrite in granular bainite and bainitic ferrite laths in a thermo-mechanically processed low-Si, high-Al transformation-induced plasticity steel. The efficacy of the ferrite morphologies segmentation procedure was verified by transmission electron microscopy. The variation in carbon content between the ferrite in granular bainite and bainitic ferrite laths was explained on the basis of carbon partitioning during their growth.

1. Introduction

Advanced high strength transformation-induced plasticity (TRIP) steels were mainly developed for automotive applications as they possess high strength–ductility ratios, formability and energy absorption properties [1,2]. They are characterised by a complex multiphase microstructure comprising retained austenite, martensite, polygonal ferrite and carbide-free bainites [3–5]. Although there are different terminologies in use [6–11], it is generally accepted that during the continuous cooling or isothermal holding of low carbon steels, the formation of intermediate austenite decomposition products (between diffusional ferrite/pearlite and diffusionless martensite) occurs. In TRIP steels, they are usually termed as granular bainite and bainitic ferrite. Here granular bainite is defined as carbide-free bainite with irregular-shaped ferrite or ferrite plates and dispersed blocky martensite/retained austenite constituent. On the other hand, bainitic ferrite is the arrangement of ferrite laths separated by layers of retained austenite and/or martensite [7,10–12]. Both ferrites in these two carbide-free bainitic morphologies exhibit a much higher dislocation density than polygonal ferrite as well as a supersaturation in carbon [13–17].

Under conventional electron back-scattering diffraction (EBSD) acquisition conditions, TRIP steel microstructures are typically indexed as iron fcc (austenite) and bcc (ferrite). Depending on the TRIP steel alloy composition and thermo-mechanical processing history, the various bcc phases (martensite and polygonal ferrite) and ferrite morphologies (ferrite in granular bainite and bainitic ferrite laths) then need to be further segmented during the post-processing of the EBSD map. However, to-date the lack of a comprehensive method that consistently distinguishes between the above phases/ferrite morphologies poses a significant hurdle to furthering our understanding of the complex interplay between them during loading.

Over the past 15 years, the methods to segment phases/ferrite morphologies have relied on various analytical tools that either: (i) quantify the conditions under which the electron back-scattering pattern (EBSP) was acquired, or (ii) make use of the quality metrics of the acquired EBSP after Hough transformation (Table 1). The parameters that describe the conditions under which the EBSP was acquired are the least used and include the confidence index (CI) and the pattern misfit angle (PM). The CI

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Table 1
The types of EBSD-based segmentation procedures undertaken to-date on multi-phase steels.

Segmentation method	Steel type	Steel composition (wt%)	Phases/constituents	Ref.
Thresholding the distribution of one parameter				
IQ/PQ/BC	TRIP	Fe–1.57Mn–1.46Si–0.91C and Fe–1.57Mn–1.23Al–0.34Si–0.31C	Polygonal ferrite, ferrite in bainite	[22]
		Fe–1.8Mn–1.51Si–0.2C	Polygonal ferrite, martensite	[26]
		Fe–1.5Mn–1.5Si–0.2C	Polygonal ferrite, ferrite in bainite	[27]
		Fe–1.48Mn–1.08Al–0.28Si–0.27C	Polygonal ferrite, ferrite in bainite	[28]
		Fe–1.6Mn–1.28Si–0.12C	Polygonal ferrite, ferrite in bainite	[29]
		Fe–1.5Mn–1.5Si–0.6C	Ferrite in bainite, martensite	[30]
		Fe–1.9Si–1.43Mn–0.21C	Ferrite in bainite, martensite	[43]
	DP	Fe–3.28Ni–0.12C	Polygonal ferrite, martensite	[23,24]
		Fe–0.09C	Polygonal ferrite, martensite	[25]
	SAE 9254	Fe–1.43Si–0.58Mn–0.56C–0.47Cr	Ferrite in bainite, martensite	[31]
BS	LC bainite	–	Polygonal ferrite, ferrite in bainite, martensite	[20]
	TRIP	Fe–1.5Mn–1.5Si–0.2C	Polygonal ferrite, ferrite in bainite	[32]
(Sub)grain ECD	DP	–	Polygonal ferrite, martensite	[20]
3rd near neighbour KAM	TRIP	Fe–1.5Al–1.5Mn–0.2C	Polygonal ferrite, ferrite in bainite	[41]
2nd near neighbour KAM	TRIP	Fe–1.9Si–1.43Mn–0.21C	Ferrite in bainite, martensite	[43]
Normalised EDS carbon counts	TRIP	Fe–1.5Al–1.5Mn–0.2C	Polygonal ferrite, ferrite in bainite	[44]
Multi-peak modelling of the distribution of one parameter				
IQ/PQ/BC	IF	Fe–0.15Mn–0.002C	Polygonal, non-polygonal, acicular and bainitic ferrite, martensite, carbon-rich micro-constituents	[34–36]
	DP	Fe–1.55Mn–1.09Al–0.15C		
	HSLA	Fe–1.3Mn–0.078C		
	TRIP	Fe–1.5Mn–1.5Si–0.2C–0.2Ni	Proeutectoid ferrite, ferrite in bainite	[37]
		Fe–23.94Mn–0.86Cr–0.51C–0.28Si–0.14Ni	Polygonal ferrite, ferrite in bainite, martensite	[38]
Thresholding the distributions of two parameters				
CI and IQ/PQ/BC or IQ/PQ/BC and (sub) grain size or BS and (sub) grain size	DP	–	Polygonal ferrite, martensite	[20]
CI and IQ/PQ/BC	–	Fe–1.39Mn–0.69Cr–0.1Si–0.08C	Polygonal ferrite, ferrite in bainite, martensite	[33]
Average (sub)grain IQ/PQ/BC and BS	–	Fe–2.2Mn–1.0Si–0.06C	Polygonal ferrite, martensite	[40]
Multi-peak modelling of average (sub) grain IQ/PQ/BC and GAM	TRIP	Fe–1.8Mn–0.5Si–0.2C	Polygonal ferrite, ferrite in bainite, martensite	[40]
Thresholding the distributions of multiple parameters				
Average (sub) grain BS, GOS, (sub) grain aspect ratio and area	– –	Fe–1.9Mn–0.2Si–0.2Cr–0.15C and Fe–0.93Mn–0.7Cr–0.2Si–0.07C	Polygonal ferrite, ferrite in bainite, martensite	[45]
Boundary misorientation profiles, (sub)grain size, aspect ratio and average internal misorientation	CASTRIP	Nb-free, 0.04 Nb, and 0.08 Nb	Polygonal, non-polygonal and acicular ferrite, ferrite in bainite	[46]

involves a Kikuchi band triplet voting scheme such that within a given inter-planar angular tolerance, the ratio between the candidate orientation with the highest number of votes and the total number of votes is regarded as the most likely solution [18]. Once a solution is selected, the PM is used to calculate the mean angular deviation between the positions of the simulated and experimental EBSPs.

On the other hand, the quality metrics of the acquired EBSP that are derived from Hough transformation include the image quality (IQ, also known as the pattern quality (PQ) or band contrast (BC)) and the band slope (BS). The IQ/PQ/BC defines the average intensity of the Hough peaks [19] whereas the BS denotes the average slope of the intensity change between the Hough peaks and their surrounding background [20]. In practice, the IQ/PQ/BC and BS are greyscaled and binned to a byte range between 0 (black) to 255 (white). Structures with elastically distorted lattices, higher density of crystalline defects or residual stresses (causatives that can be linked to the transformation of austenite to bainite or martensite) present with blurred Kikuchi band edges, diffuse Hough peaks and appear darker with lower IQ/PQ/BC and BS values [21]. Conversely, polygonal ferrite presents with sharper Kikuchi band edges, more intense Hough peaks and has higher IQ/PQ/BC and BS values.

The IQ/PQ/BC are the most commonly used parameters to distinguish between features with varying dislocation density by thresholding the distribution between areas of low and high contrast. In order to accomplish this semi-quantitatively, the thresholding procedure relies on the presence of a clear and specific inversion point between individual peaks of the IQ/PQ/BC distribution. For example, in the case of a bimodal distribution, the threshold is conventionally defined as the lowest value between the two distinct peaks. Taking advantage of this statistical peculiarity, one of the first EBSD studies on Fe–1.57Mn–1.46Si–0.91C and Fe–1.57Mn–1.23Al–0.34Si–0.31C (wt%[1]) TRIP steels by De Meyer et al. [22] used the IQ/PQ/BC to distinguish the ferrite in bainite from polygonal ferrite. The same technique was used to observe/quantify the volume (or area) fractions of: (i) polygonal ferrite and martensite in Fe–3.28Ni–0.12C [23,24], Fe–0.09C dual phase [25], and Fe–1.8Mn–1.51Si–0.2C quench and partitioned TRIP steels [26], (ii) polygonal ferrite and the ferrite in bainite in Fe–1.5Mn–1.5Si–0.2C [27], Fe–1.48Mn–1.08Al–0.28Si–0.27C [28] and Fe–1.6Mn–1.28Si–0.12C [29] TRIP steels, and (iii) the ferrite in bainite and martensite in Fe–1.5Mn–1.5Si–0.6C [30] and Fe–1.43Si–0.58Mn–0.56C–0.47Cr SAE 9254 steels [31].

The BS parameter has been applied less often. Kwon et al. [32] used the BS to distinguish the ferrite in bainite from polygonal ferrite in austempered Fe–1.5Mn–1.5Si–0.2C TRIP steel. The low BS of the ferrite in bainite was ascribed to its formation during the

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[1] Throughout the text, chemical compositions are in weight per cent unless specified otherwise. With the exception of C, elements <0.1 wt% are not stated.