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EBSD on bainitic steel to assess parent austenite state after multi-pass hot rolling: Textural analysis versus reconstruction of prior grains

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ABSTRACT

Owing to inter-phase orientation relationship, EBSD analysis of martensitic or bainitic steel enables reconstruction of prior grains. Thus, assessment of the treatment conditions remains possible even if the chemical etching cannot properly reveal the parent structure. However, such an approach is hardly applicable to the industrial modes of multi-pass rolling. Unlike a single thickness reduction, small strains per pass followed by a kind of annealing in inter-pass pauses cause specific mechanisms of austenite recrystallization so that the latter becomes difficult to be assessed in morphological terms. At the same time, the textural analysis enables estimation of the parent state using whether the texture of reconstructed austenite or the measured transformation texture. When tested on low carbon bainitic steel, both methods lead to close estimates of the parent texture and thus support each other.

KEYWORDS

austenite • bainite • martensite • martensite • hot rolling • prior grains • transformation texture • EBSD

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Introduction

According to orientation relationships (OR) pronounced in martensitic and bainitic steels [1–3], the transformation texture measured at room temperature is indicative of the proportion between deformation and recrystallization components in the *parent* texture. Thus, the hot rolling effect on austenite states before the direct quenching keeps detectable regardless of the prior grain morphology. Such an advantage is very important for low carbon steels where a chemical etching to image prior grains is rather laborious and not always efficient. However, the considered textural method originally based on X-ray diffraction (XRD) data [4,5] did not attract due regard because of some limitations considered in our previous article [6]. Instead, to assess a shape of prior grains, the latter are commonly reconstructed from EBSD data [7–14] with allowance for a certain OR.

Avoiding the reconstruction of austenite grains, use of EBSD data to assess the parent texture rather than structure greatly simplifies computations while averaging out local measurement errors [6]. Besides, it allows to get rid of the above-mentioned shortcomings inherent in XRD technique. These advantages particularly gain in significance in the general case where deformed and recrystallized austenite fractions can turn out comparable so that the grain morphology is hard to quantify. Apart from these reasons, a principal limitation of the morphological estimate appears in the *multi-pass* modes of industrial hot rolling. In this case, a combination of concurrent recrystallization mechanisms during the sequence of strains followed by a kind of annealing in pauses between them notably weakens the effect of rolling conditions on grain shapes [15–19]. Regardless of related explanations [16,18] remaining a subject of dispute, the considered regularity in itself supports the alternative textural approach to parent states of steel.

Following [5], to evaluate specific contributions to the transformation texture appearing from deformation and recrystallization components of the parent texture, we will make use of the virtual Bain relationship [20] since various actual ORs generally spread around it. With orientations expressed by Euler angles (φ_1, Φ and φ_2), Figure 1 illustrates the above-mentioned orientation transformations by respective ODF sections at φ_2 = 45°. Unlike a strong influence of presumed OR on the grain reconstruction [7–10], such an implicit allowance for variations of real OR will not notably affect assessments of the parent orientation statistics. Moreover, determination of any presumably precise OR is not realistic because the result depends on an analyzed EBSD area and can vary even within prior grains [21,22]. This ambiguity particularly aggravates at deformed grains owing to the orientation inhomogeneity in their substructures [23]. In this case the reconstruction has to rely on some intuitive compromise between the locality of OR and its significance suggesting a large enough analyzed domain.

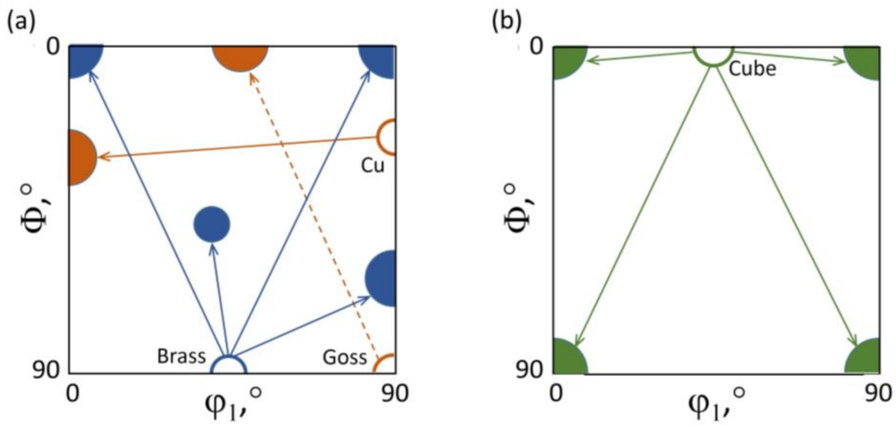

Fig. 1. Sections of ODF at φ_2 = 45° illustrating the transformation of main texture components according to the Bain OR for (a) deformed and (b) recrystallized states of hot rolled austenite. Parent and transformed components are represented by empty and filled circles, respectively

To quantify austenite states formed in multi-pass hot rolling, measured textural parameters should be compared with reference values corresponding to certain recrystallization degrees as confirmed by independent methods. In the present work both the completely deformed and recrystallized states of austenite will be prepared by single passes of hot rolling in a medium carbon martensitic steel where specific shapes of prior grains are easy to reveal by etching. Despite a different chemical composition of this material, it admits the method calibration as far as the Bain relationship approximates both its OR and that of the considered bainitic steel. Anyway, this difference is insignificant relative to those of model FCC alloys [4,24,25] used to mimic the parent phase of hot rolled martensitic or bainitic steel.

Since the proposed treatment of EBSD data suggests a simple alternative to the currently popular grain reconstruction, we will compare respective assessments of the parent austenite states. The comparison is possible as far as shapes of prior grains are restored together with their orientations [7–11] and resulting statistics of them represents the parent texture. The latter mostly averages out local errors sensitive to the presumed OR and hence can implicitly verify use of the Bain relationship that provides a virtual center for various experimental OR.

Materials and Methods

To analyze influence of multi-pass hot rolling modes on the austenite state of low carbon bainitic steel (wt. %: 0.08C, 0.21Si, 0.34Mn, 2.6[Ni+Cu], 0.59[Cr+Mo], 0.038[V+Nb]), its slabs of 250 mm thickness reheated to 1200 °C, were rolled at gradually diminishing temperatures to the thickness of 18 mm before the direct quenching in a sprinkler installation. Keeping these conditions, the rolling modes still could vary in strains and temperatures at the finish stage. Limiting consideration to its last five passes, we will compare modes B_1 and B_2 providing there average thickness reductions per pass of 16 and 14 % at average temperatures of 913 and 977 °C, respectively. According to previous experiments [6], B_1 results in a stronger work hardening of austenite that elevates the transformation start temperature and hence provides softer bainite unlike the more lath-like bainite of B_2. Additionally, in order to obtain a bainitic state with a weakened rolling texture, a sample of B_2 was reheated to 950 °C and quenched in water. Therefore, the initial texture has been dissipated by way of α–γ–α transformation. This mode has been marked as B_3.

As noted in the introduction and further confirmed in this paper, effects of the multi-pass rolling, hard to analyze in terms of the grain morphology, still are perceptible by the material texture. The latter in turn satisfactorily complies with grain shapes after a *single* rolling pass [4,26] so that revealed parent structures enable the calibration of textural parameters. To make use of this expedient, we will consider medium carbon martensitic steel (wt. %: 0.35C, 0.3Si, 1.8[Ni+Mn], 0.75[Cr+Mo], 0.04[V+Nb], 0.003B) since its prior grains are easy to image by etching in Marshall's reagent [27] at room temperature. Samples of this reference material reheated to 1150 °C have been hot rolled by single passes to a thickness reduction of 35 % at temperatures 900 and 1100 °C. According to [26], the whole parent phase of this steel proves to be deformed or fully recrystallized at the lower or the higher rolling temperature, respectively.

Sections of the samples prepared by usual metallographic procedures were then subjected to electrolytic polishing in perchloric acid-ethanol solution at 0 °C. Using SEM Lyra 3-XM at an accelerating voltage of 20 kV, EBSD orientation data are collected by Channel 5 software at various scanning steps. Textures of martensitic and bainitic steels were composed over areas of 2.25 and 3 mm^2, respectively, with a step of about 1 µm. Then, the step was refined to 0.1 or 0.5 µm for the bainitic and martensitic steel, respectively, in order to reconstruct prior grains. Treatment of the orientation data, including the reconstruction of austenite texture and structure, was conducted using MTEX toolbox [12] for MatLab.

Results and Discussion

Martensitic steel hot rolled by single pass

Revealed by the chemical etching on martensitic steel, structures of its parent austenite after single passes of hot rolling at different temperatures are shown in Fig. 2(a,b). The distinction between deformed and recrystallized prior grains is apparent here owing to their flattened and equiaxed shapes, respectively. Results of the grain reconstruction from EBSD represented in Fig. 2(c,d) satisfactorily comply with the images in Fig. 2(a,b). Moreover, a recrystallized state indicated in Fig. 2(b) by the grain shape is additionally justified in Fig. 2(d) by the orientation uniformity, that is, by the absence of substructure within reconstructed grains.

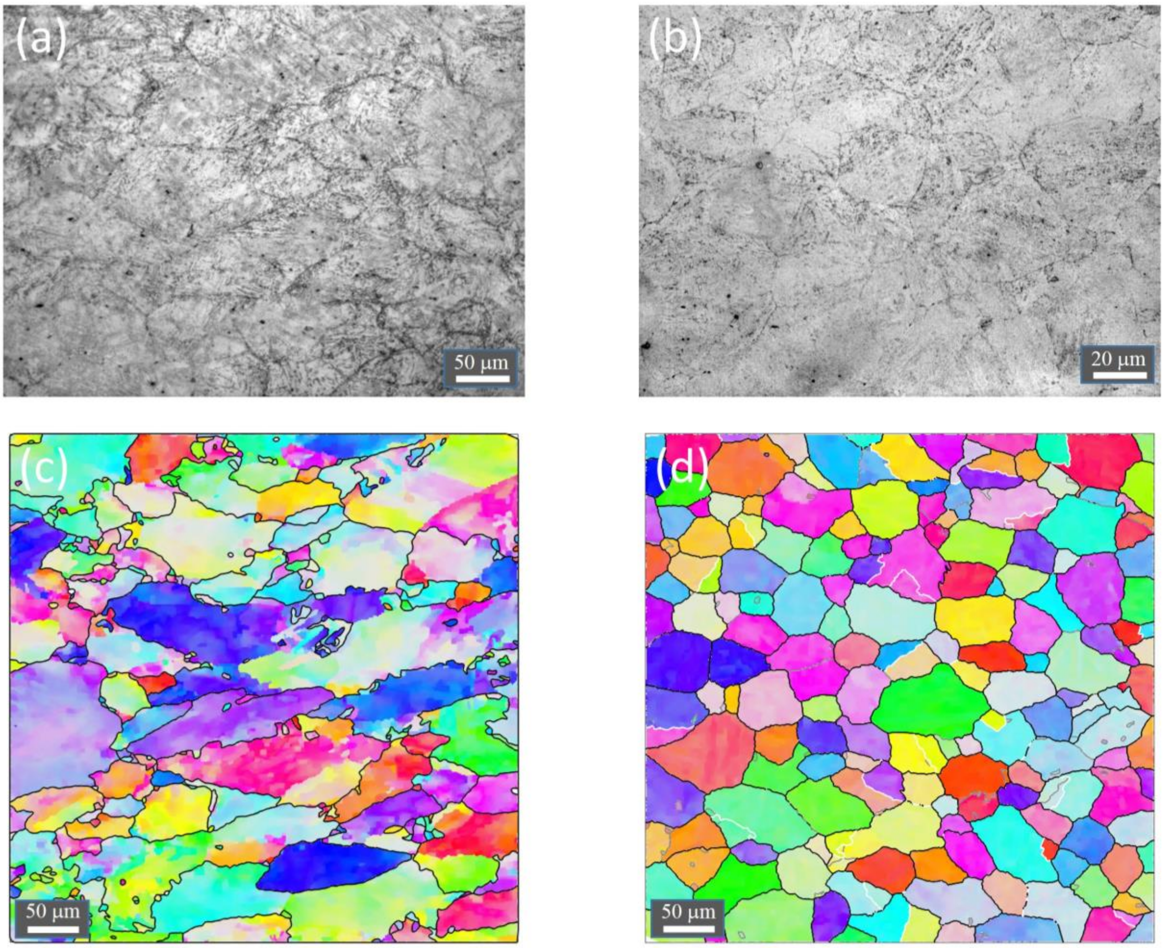

Fig. 2. Deformed (a,c) and recrystallized (b,d) parent structures of martensitic steel hot rolled by a single pass: image of prior grains revealed by chemical etching (a,b) and respective orientation (IPF) maps reconstructed from EBSD data (c,d). Coloring of boundaries on the orientation maps: low angle − gray; random high angle − black; twin − white

Figure 3 shows the (110) pole figures obtained for two structural states of the martensitic steel (the transformation textures) and the (111) pole figures computed for the reconstructed austenite. Note that, as long as {110} planes of α phase are approximately parallel to the {111} of γ phase in accordance with the inter-phase OR [1], close correlation between the (110) pole figures for the martensite texture and the (111) pole figures for the prior austenite texture exists [4].

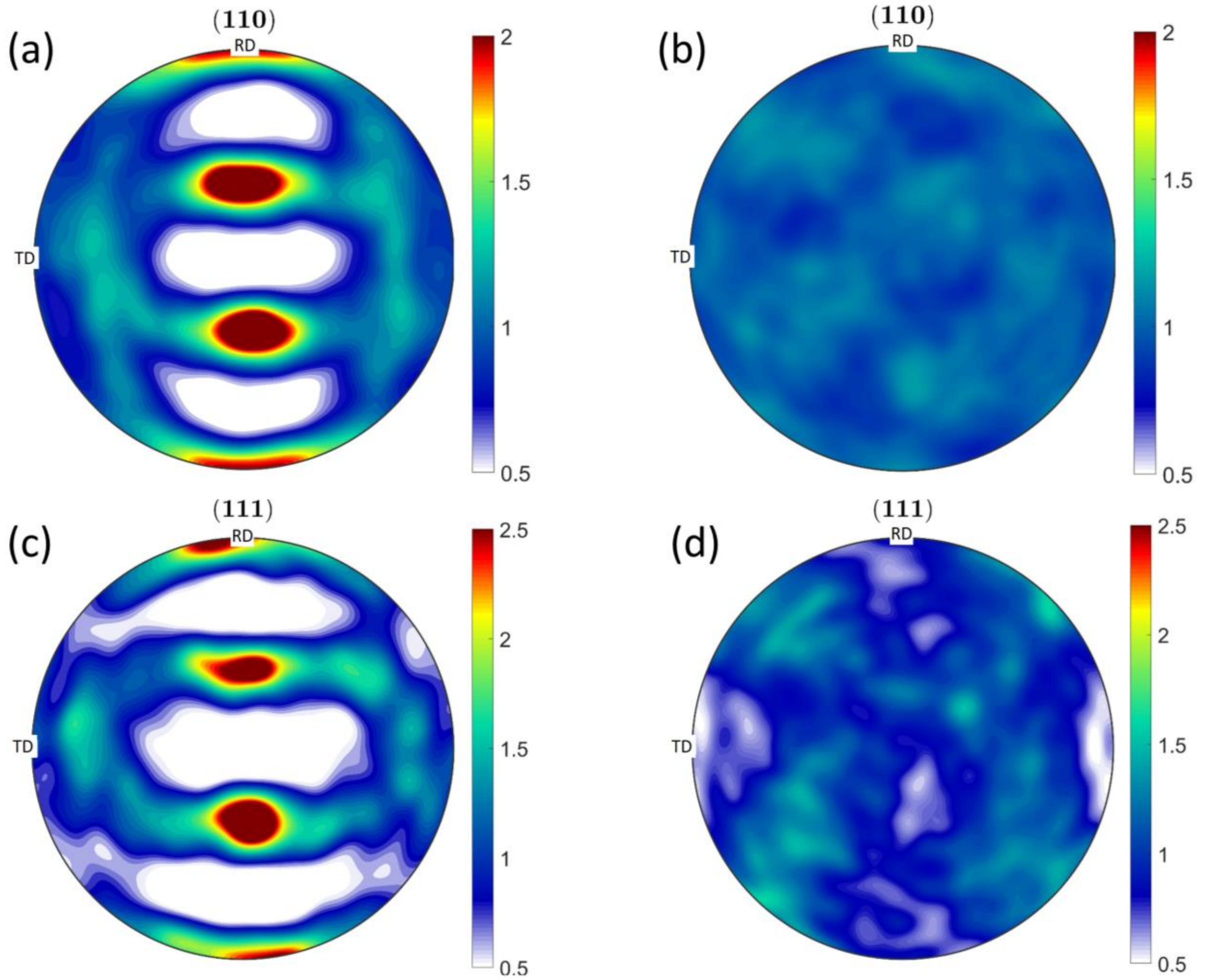

Fig. 3. Pole figures for measured transformation textures of martensitic steel (a,b) and its reconstructed parent textures (c,d). Figures (a,c) and (b,d) correspond to the deformed (M1) and recrystallized (M2) states of parent austenite, respectively

More detailed and unambiguous representation of texture is given by the orientation distribution function (ODF) [28]. Figure 4 represents ODF sections (φ_2 = 45°) for the considered textures. In the deformed state, Fig. 4(c), austenite texture have strong Cu and Brass components (see Fig. 1), whereas the texture of recrystallized state, Fig. 4(d), is significantly dissipated and contain Cube component. Therefore, the textures confirm our above conclusions made on the basis of structure appearance.

To sum up this subsection, after the hot rolling by the single pass both the shapes of prior grains (whether revealed by etching or reconstructed from EBSD data) and the related textures of steel lead to similar assessments of the parent austenite states,

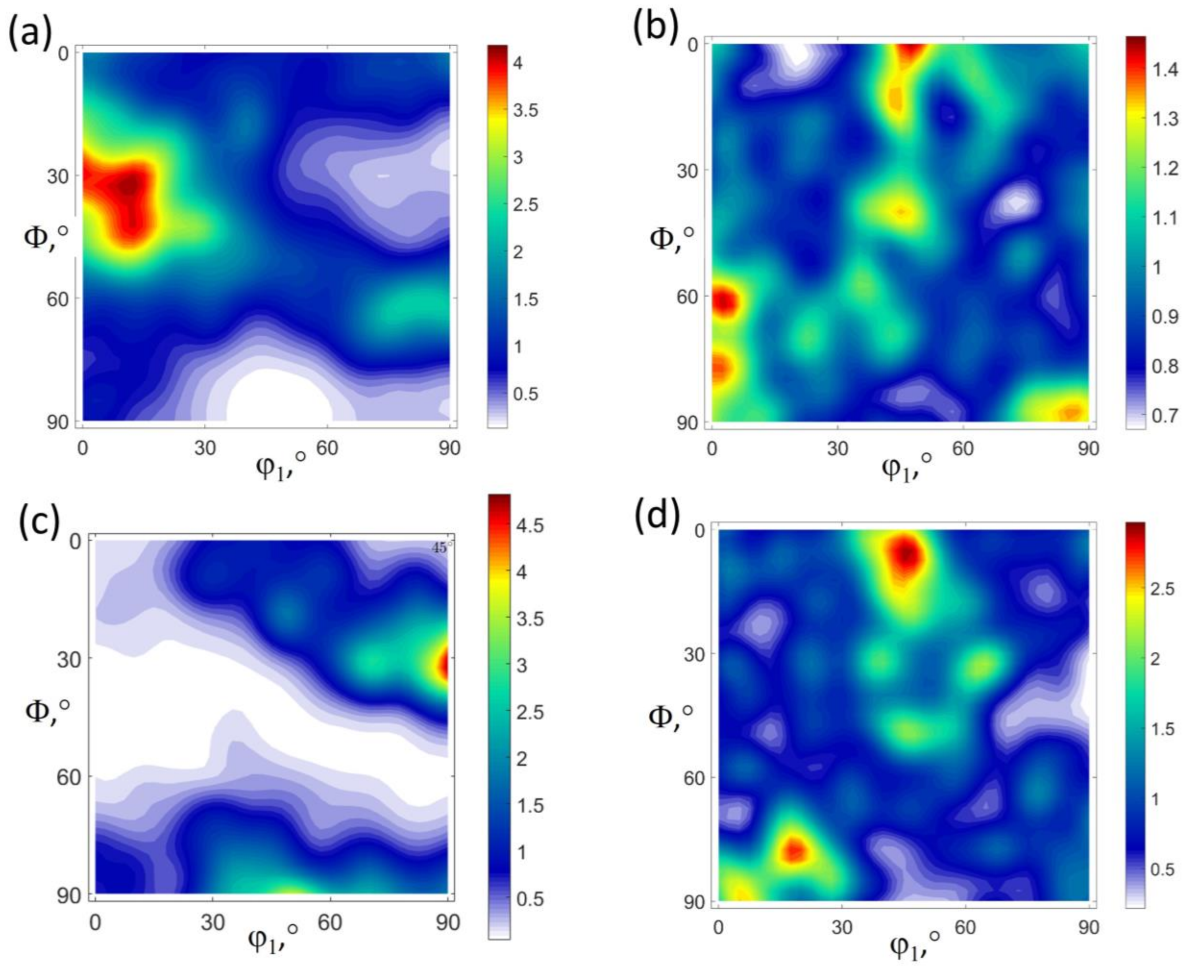

Fig. 4. Sections of ODF at φ_2 = 45° for the measured transformation textures of martensitic steel (a,b) and its reconstructed parent textures (c,d). Figures (a,c) and (b,d) correspond to the deformed and recrystallized states of parent austenite, respectively

namely, the first is deformed while the second is completely recrystallized. These two states are further used to calibrate textural data on bainitic steel.

Bainitic steel hot rolled by industrial multi-pass mode

Figure 5 shows the structure of prior austenite reconstructed in the cases termed B_1, B_2 and B_3. The latter case (Fig. 5(c)) is not in dispute since here we have austenite grains created during reverse α to γ transformation. The structures presented in Fig. 5(a,b), however, are rather difficult to interpret. Actually, in the case of mode B_1 one can see highly distorted grain boundaries as well as a misoriented substructure inside grains. At the same time, the flattening of grains that one might expect in the deformed state, is not observed. For the mode B_2, the austenite grains are less distorted that seems to indicate a greater contribution of recrystallization. However, this contribution is difficult to assess quantitatively.

The pole figures obtained on bainitic steel (Fig. 6) demonstrate that the industrial hot rolling modes mostly lead to the rolling texture, stronger in B_1 and weaker in B_2. In the case of B_3, where the texture is very weak, the subtle signs of the rolling texture,

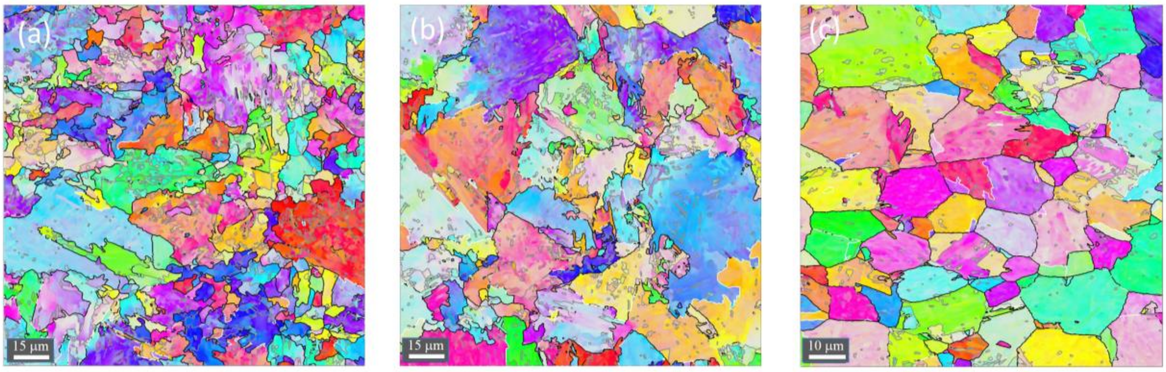

Fig. 5. Prior austenite grains reconstructed from EBSD data on bainitic steel subjected to regimens (a) B_1, (b) B_2 and (c) B_3. Coloring of boundaries on the orientation maps: low angle – gray; random high angle – black; twin – white

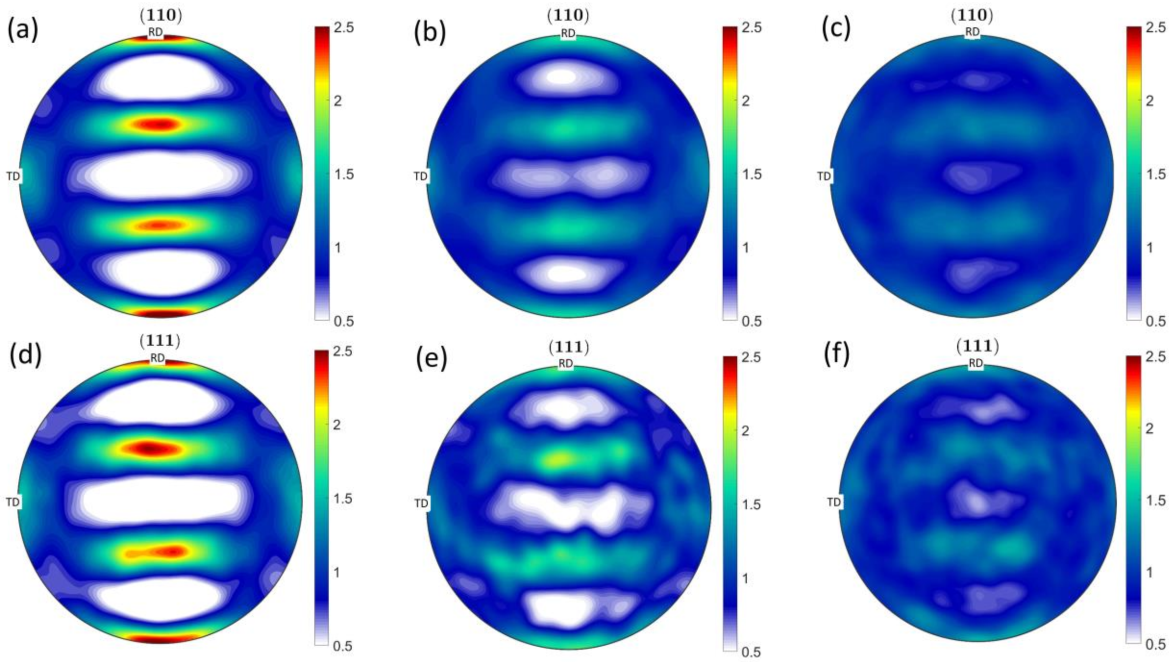

Fig. 6. Pole figures for measured transformation textures of bainitic steel (a,b,c) and its reconstructed parent textures (d,e,f). Figures (a,d), (b,e) and (c,f) correspond, respectively to the regimens B_1, B_2 and B_3

which remain visible after α–γ–α transformation, are due to a "texture memory" peculiar to bainitic steels [29].

Consider now the ODF sections (Fig. 7). For B_1, the intensities of transformed Cu and Brass components in Fig. 7(a) are close to those for the not-recrystallized austenite[1] of the martensitic steel (see Fig. 4(a)) that indicate a deformed state of austenite in this case. The reconstructed texture confirms this suggestion in view of the strong Cu and Brass components. At the same time, a Cube component also takes place in Fig. 7(d). Though

[1] The intensities of main texture components are even stronger than in the case of martensite, apparently because of the larger accumulated strain during hot rolling [6].

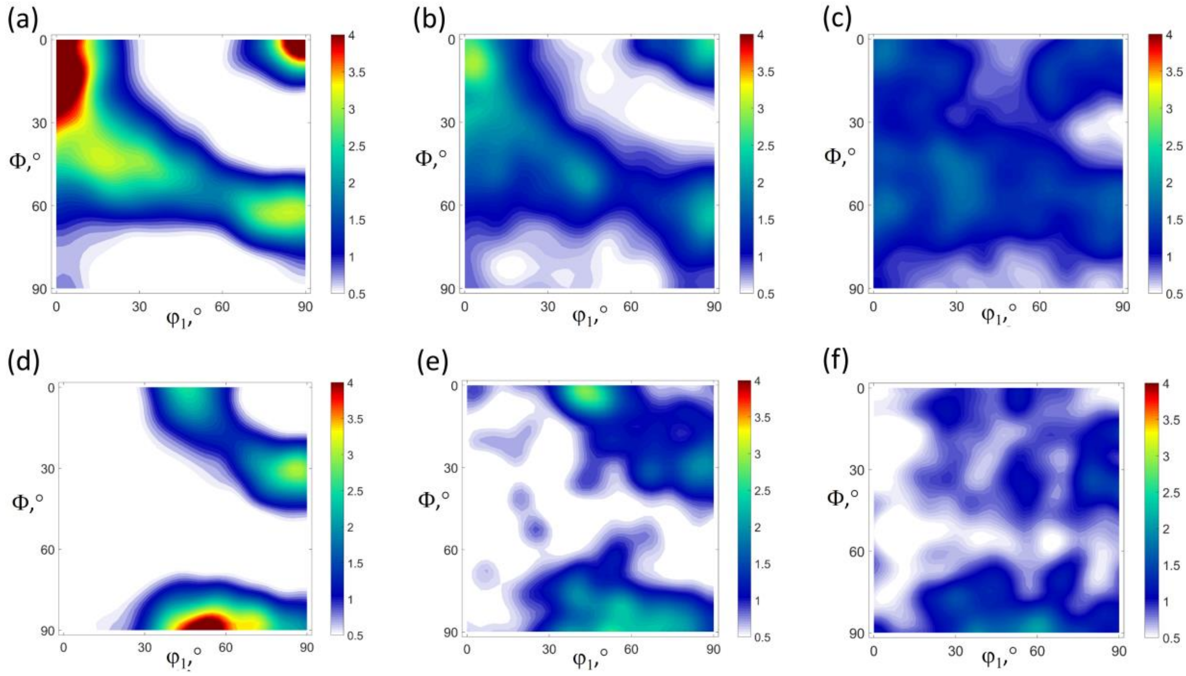

Fig. 7. Sections of ODF at φ_2 = 45° for the measured transformation textures of bainitic steel (a,b,c) and its reconstructed parent textures (d,e,f). Figures (a,d), (b,e) and (c,f) correspond, respectively, to the regimens B_1, B_2 and B_3

very weak, it indicates, together with the morphological features of austenite grains (Fig. 5(a)), an occurrence of certain recrystallization. The conservation of pronounced rolling texture in the samples of bainitic steel allows us to assume that those recrystallization is associated mostly with local migration of grain boundaries, similar to what happens during continuous recrystallization [30]. A deformation texture is known to mostly retain during such a structural transformation, while a strengthening of Cube component may be caused by a preferential growth of Cube-oriented regions [31].

For B_2, the texture components related to the rolling are considerably weaker than for B_1, both in the transformation and parent textures, while the Cube component is stronger. This confirms an increased contribution of recrystallization to the austenite structure formation during this mode of hot rolling.

Therefore, it turned out that, in the case of multi-pass rolling of bainitic steel, the textural analysis enables to assess structural state of parent austenite more unambiguously than the reconstruction of austenite grains. Moreover, not only the reconstructed austenite texture but even the transformation texture gives this possibility. With regard of this finding, a simple scalar parameter is suggested and verified in the next section for quantification of those assessment.

Quantification of austenite states in textural terms

To introduce a single scalar [26] indicative of the whole texture, we will allow only for two components of the latter, which are unambiguous and most strong. Specifically, at the deformed state of parent austenite (Fig. 1(a)) they are Brass and Copper components, whereas in the respective transformation texture the transformed Copper and the right lower constituent of transformed Brass should be considered. Accumulation of rolling strains is then expressed by textural parameter

$t = 0.5(p_1 + p_2)/r - 1$, (1)

where p_1 and p_2 are probability densities averaged within 15° deviations from virtual centers of the two considered components and r is probability density in case of the random orientation distribution [32]. Note that austenite recrystallization, if any, is also reflected by t insofar far as probabilities of all texture components sum to unity. Derived from measured transformation textures and statistics of the reconstructed prior grain orientations, the considered parameters are listed in Table 1 with subscripts α and γ, respectively. In turn, states B_1–B_3 of bainite follow the gradual texture weakening in accordance with strain degree stored in austenite before its transformation.

Table 1. Characteristics of austenite states as derived from the transformation (α) and parent (γ) textures of steel

Parent state	Textural parameter		Recrystallization degree, %	
	t_α	t_γ	R_α	R_γ
M_1	3.7	3.8	0*	0*
M_2	0.7	-0.1	100*	100*
B_1	4.0	3.6	0	5
B_2	2.5	2.0	40	46
B_3	1.6	1.6	–	–

*Calibration according to the grain morphology

Let the completely deformed and recrystallized austenite states appear at $t \geqslant t_d$ and $t \leqslant t_r$, respectively, where reference t_α and t_γ are found by metallographic methods. Then, using a kind of the lever rule as proposed in [26], the recrystallization degree is roughly evaluated by:

$$R = \begin{cases} 1, & t \leq t_r \\ 0, & t \geq t_d \\ (t_d - t)/(t_d - t_r), & t_r < t < t_d \end{cases} . \quad (2)$$

To discriminate between transformation (measured) and parent (reconstructed) textures in what follows, corresponding estimates of t and R will have appropriate subscripts. As to t_d and t_r, they are determined in previously considered special states M_1 and M_2, respectively. Concerning mode B_3, values $R_\alpha = 70$ % and $R_\gamma = 57$ % formally calculated according to Eq. (2) have not been placed in Table 1, since a true recrystallization did not occur in this case. According to the listed results, the two compared methods satisfactorily correspond to each other. Thus, plausible assessments of the parent state are possible without the reconstruction of prior grains. Obviously, rapidly developing methods of reconstruction remain in demand since *morphology* of the austenite structure undoubtedly affects the kinetics of transformation during subsequent cooling. In this regard, a simplified approach based on the Bain relationship finds one more application as the tool to verify grain reconstruction algorithms in textural terms.

Conclusions

Characterization of parent austenite in the samples of bainitic steel treated by multi-pass hot rolling has been performed using EBSD analysis of bainite as well as EBSD-based reconstruction of parent austenite. The reconstruction of austenite structure has showed that considerable recrystallization proceeded during last passes of the rolling. However, this is not a usual "discontinuous" recrystallization [31], which includes nucleation of new grains and their growth at the expense of neighboring deformed grains. Judging from both textural and structural analysis, the observed mode of recrystallization is mostly reduced to the local migration of boundaries, similar to the continuous recrystallization of heavily deformed metals.

In spite of apparent occurrence of recrystallization, it is difficult to assess its degree in multi-passed hot rolling from the reconstructed austenite structure. At the same time, such an assessment can be made based on the crystallographic texture. To do this, we have introduced a scalar parameter dependent on the intensity of main texture components. To calibrate this textural parameter, a martensitic steel in two conditions has been used; in the first condition the parent austenite was deformed while in the second it was completely recrystallized. Such an analysis can be performed based on the transformation texture or the reconstructed austenite texture, and these two methods were shown to agree satisfactorily. Thus, assessment of the parent austenite state is possible even without the reconstruction of prior grains.

CRediT authorship contribution statement

Alexander A. Zisman: writing – review & editing, supervision; **Nikolay Yu. Zolotorevsky**: writing - original draft, investigation; **Dmitri A. Petrov**: investigation ; **Sergey N. Petrov**: data curation .

Conflict of interest

The authors declare that they have no conflict of interest.

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