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Combined effect of stress and strain on crystallographic orientation of bainite

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Abstract

The combined influence of prior plastic strain in the austenite, and applied stress in the course of the transformation, on the crystallographic texture of a bainitic steel was studied in this work. The experimental data were obtained using Electron Back Scatter Diffraction (EBSD) method and analyzed using two methodologically different approaches. It was concluded that the plastic deformation of the parent austenite grains could suppress variant selection in the bainite despite maintaining an externally applied load throughout the bainitic transformation.

1- Introduction

Bainite forms in steels by transformation of the parent austenite, induced by a homogeneous plastic deformation which does not require diffusion [1–4]. Hence, bainitic transformation and ordinary plastic deformation are somehow similar. For instance, in both cases certain crystallographic planes and directions (*i.e.* variants) are favoured. The favouring of certain variants over the others is known as "variant selection". The crystallography of each plate of bainite can be described in terms of a mathematically connected set of habit planes, orientation relationships with the parent austenite, and the shape deformation [5]. The interaction between the applied stress and the transformation can be treated by adding a mechanical driving force

(G_{MECH}) to the chemical term (G_{CHEM}) which would be the driving force for the transformation even in the absence of applied stress.

Hase *et al.* studied the effect of applied compressive stresses on the bainite start-temperature and variant selection in a carbide-free bainitic steel [6]. The work showed that the applied compressive stress of about 200 MPa raised the transformation start-temperature and led to micro-structural alignment of the bainite sheaves. The optical micrographs clearly confirmed that the majority of bainite sheaves were formed on the planes of maximum shear stress (*i.e.* 45° angle to the applied compressive load), and the higher the applied load the higher the abundance of aligned sheaves. Visual examination of the electron back scatter diffraction (EBSD) maps revealed that certain crystallographic orientations were favoured within some large regions containing parallel bainite sheaves; indicating the presence of a strong variant selection. No quantitative assessment of the variant selection was carried out in Hase *et al.* work.

In more recent work, Shirzadi *et al.* investigated the influence of plastic strain alone (*i.e.* without any applied stress during the transformation) on the crystallographic orientation of bainitic [7]. They found no strong variant selection in the bainitic steel which transformed from a plastically deformed austenite to bainite under zero applied load. This was in contrast with Bokros and Parker's work on a single crystal austenite in which a strong variant selection in martensite was observed due to prior plastic deformation of the parent austenite [8]. It is possible that the complexity of slip systems in the polycrystalline steel used by Shirzadi *et al.*, where multiple slip systems must operate in order to maintain continuity, led to the lack of strong variant selection. Whereas, in Bokros and Parkers' work, the observed variant selection occurred because of the anisotropic nature of the dislocation debris in the austenite single crystal.

The purpose of the present work was to study the combined influence of (1) prior plastic strain in the parent austenite, and (2) applied stress in the course of the transformation, on the crystallographic texture of bainite.

2- Crystallographic orientation in steels

The room temperature microstructure and texture of a steel mostly depend on its composition, thermo-mechanical history and initial crystallographic orientation of the parent austenite at the elevated temperature prior to its transformation to a low temperature phase, e.g. ferrite or martensite. When austenite transforms to ferrite by a reconstructive mechanism, the product phase nucleates heterogeneously at austenite grain boundaries. Although a reproducible, low energy orientation relationship is expected to exist between the ferrite and that of the parent austenite grains, it is possible that the ferrite simultaneously adopts this orientation with more than one austenite grain. On the other hand, in displacive transformations the crystal structure of the parent austenite is deformed into that of the product without the need for any diffusion. In displacive transformations, the coordinated movements of atoms cannot be sustained across the grain boundaries. Hence, it is reasonable to assume that the product is confined to the parent grain with which it has an orientation relationship [9].

In the case of displacive transformations such as martensite and bainite[1] certain sets of the orientation relationship, shape deformation and habit planes can be defined using the theory of martensitic transformation. Such transformation are dominated by strain energy due to the shape deformation, therefore many of the crystallographic variables cannot be varied independently [10]. Hence, having assumed that the product phase grows in the same parent

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[1] Some crystallographers argue that formation of bainite is also a reconstructive transformation since it requires breaking up the atomic bonds and limited amount of diffusion.

crystal in which it nucleates, the texture of final phase can be predicted once the orientations of the parent crystals are known [11].

In order to study and predict the evolving textures in polycrystalline steels, the original crystallographic orientation of the austenite has to be known. Various simulation techniques and experimental methods are used to determine the texture of retained austenite [12-15]. For instance, advanced X-ray and neutron diffraction methods can be used to determine the texture of the parent austenite at 950°C prior to its transformation to low-temperature phases [16].

3- Determining variant selection

In this work, two methodologically different approaches were used to investigate the presence (or lack) of the variant selection in a bainitic sample, which was formed under a compressive stress from a plastically deformed parent austenite. In the first approach ARPGE software were used to reconstruct the orientation of the parent austenite grains followed by a statistical analysis of the bainite texture [17,18]. The second approach relies on the micro-texture development within individual austenite grains as a function of the direction of the applied compressive stress. The micro-texture of the grains could be illustrated and compared using the corresponding pole figures. The details of the second approach were given elsewhere [7].

Statistical approach

The ARPGE software is capable of determining the crystallographic orientation of austenite grains using the EBSD data acquired from the room temperature phase (*i.e.* bainite) and without requiring any experimental data on the parent austenite grains [17,18].

The reconstruction of parent austenite is performed by (a) checking if the experimental misorientations between the BCC grains are close to theoretical misorientations (*i.e.* operators),

(b) checking if the composition of the operators corresponds the theory (groupoid composition), (c) deducing the indexes of the variants and (e) calculating the orientation of the parent austenite grains- see Ref [18] for more details. Finally, the global pole figures corresponding to the texture of the parent grains are drawn, and the frequencies of the detected variants and used operators are represented on columnar charts. If the frequencies of variant indexes and/or operators between the neighboring grains are high, then one can conclude that the variant selection has most likely occurred. The flow chart in Fig. 1 shows the procedure used to determine whether variant selection occurred in the sample studied in this work.
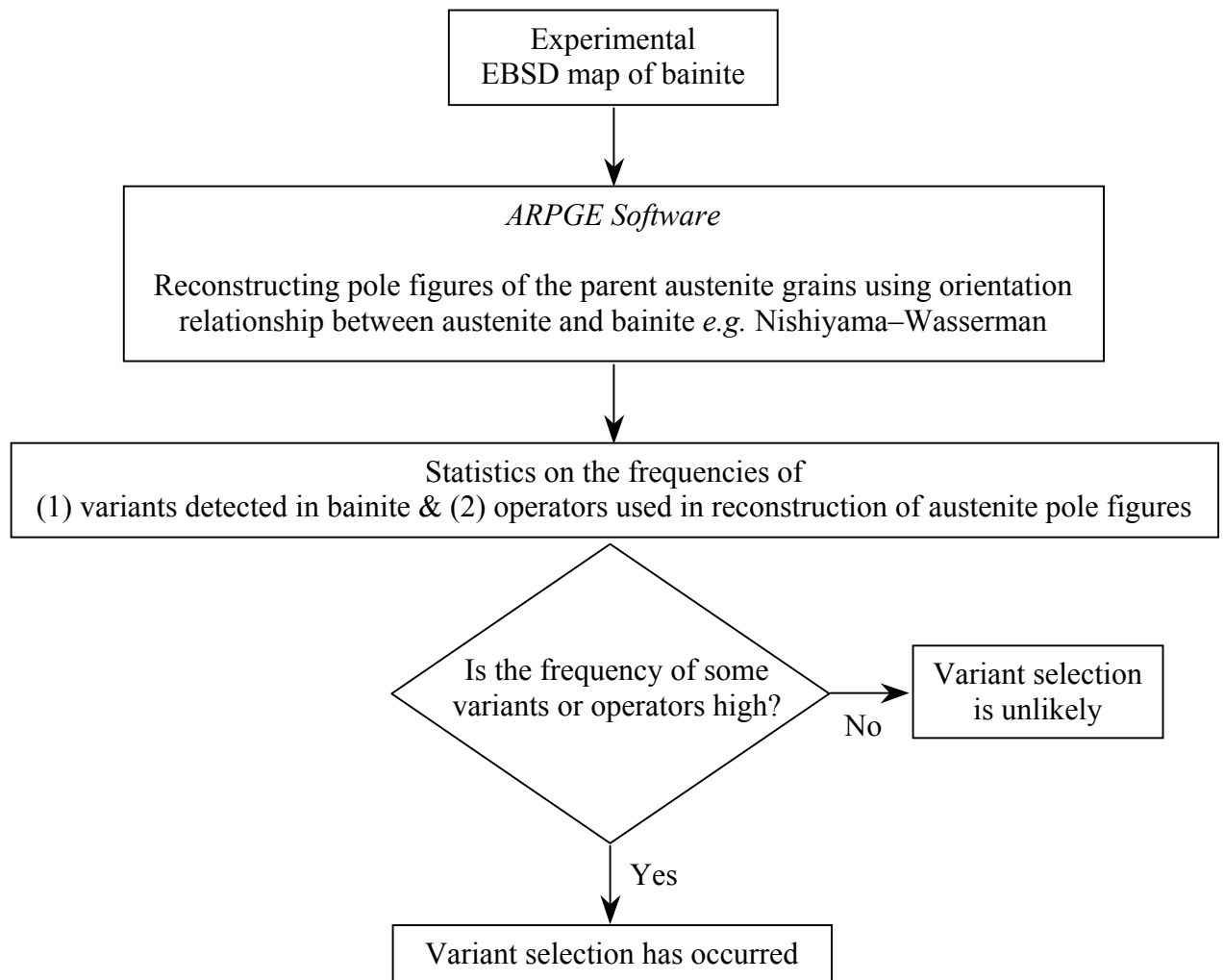

Fig. 1: Procedure of analyzing variant selection in a fully bainitic steel using EBSD data.

Micro-texture approach

In this method we used representative examples of the orientations of bainite within 4 individual austenite grains. The phenomenological theory of martensite crystallography gives a complete description of the mathematical connection between the orientation relationship, the habit plane and the shape deformation for each plate that forms by a displacive transformation. The most common application of this theory is to martensitic transformations but it applies equally well to bainite in steels [19]. Using the crystallographic set needed to describe each plate of bainite [20], the measured orientation of the austenite grain, and a knowledge of the applied stress it is possible to calculate which of the 24 possible crystallographic variants is favoured by the applied stress – see Ref. [7] for more details.

4- Experimental procedure

The chemical composition of the steel used in this work was Fe–0.79C–1.56Si–1.98Mn–0.002P–1.01Al–0.24Mo–1.01Cr–1.51Co wt%. This is the same alloy used by Hase *et al.* [6] to study bainite growth in a fully annealed austenite under the influence of an externally applied load, and also by Shirzadi *et al*. [7] who studied the texture in bainite which formed from plastically deformed austenite under no load.

Cylindrical specimens with 8 mm diameter and 12 mm length were prepared for the experiments, which were carried out using an adapted thermo-mechanical simulator, *Thermecmastor Z*. Details of this equipment were published elsewhere [21] but the thermo-mechanical procedure, used in this work, is illustrated in Figure 2.
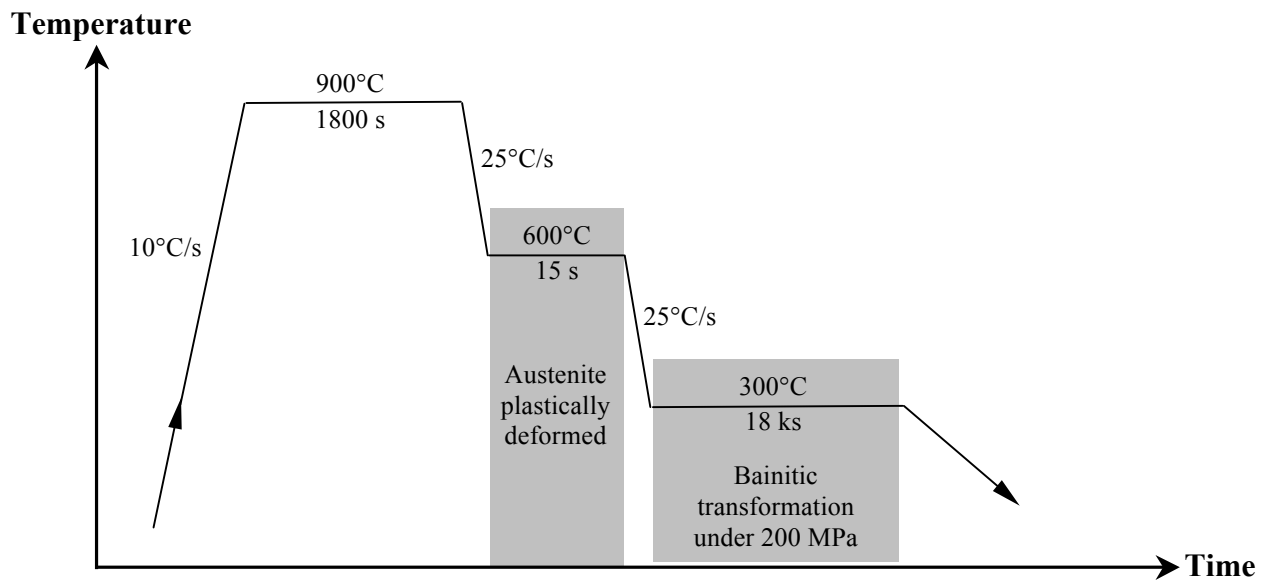
Figure 2: Thermo-mechanical processing cycle and formation of bainite from plastically deformed austenite during isothermal transformation under 200 MPa compressive stress at 300°C for 5 h.

Axial compression of cylindrical samples results in a barreling effect and a heterogeneous distribution of plastic strain when there is friction between the sample and the platens which apply the compressive force. Finite element (FEM) calculations were carried out using an assumed friction coefficient of 0.2 in order to simulate the barreling effect and determine the strain where the EBDS data were collected. The constitutive equations used in the FEM to represent the deformation of the cylindrical sample are from another steel (Fe–0.15C–0.45Mn wt%) so the results here are indicative. Figure 3 shows that the actual compressive strain in the centre of sample, where the orientation imaging experiments (EBSD) were conducted, are greater than the overall longitudinal deformation of about 10%.

< 7%

7-14%

14-20%
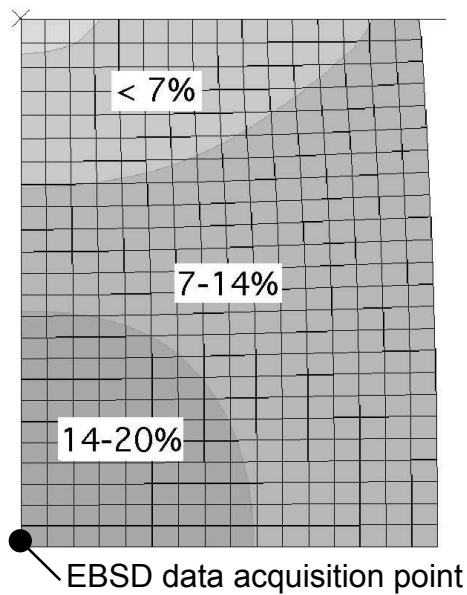
EBSD data acquisition point

Fig. 2: Finite element analysis used to estimate axial compressive strains in various parts of the test sample. The diagram represents quarter section of cylindrical samples with about 10% longitudinal strain [7].

The bainitic sample was sectioned, mechanically ground and polished using colloidal silica suspension. Crystallographic data were generated by electron backscatter diffraction (EBSD) using a CAMSCAN scanning electron microscope at a magnification of ×500 with a step size of 0.5 μm. Orientation data were acquired from the centre of the sample where the plastic strain was estimated to be about 20% - see Figures 2 & 3. Subsequent EBSD maps were generated using HKL's technology "Channel 5" software.
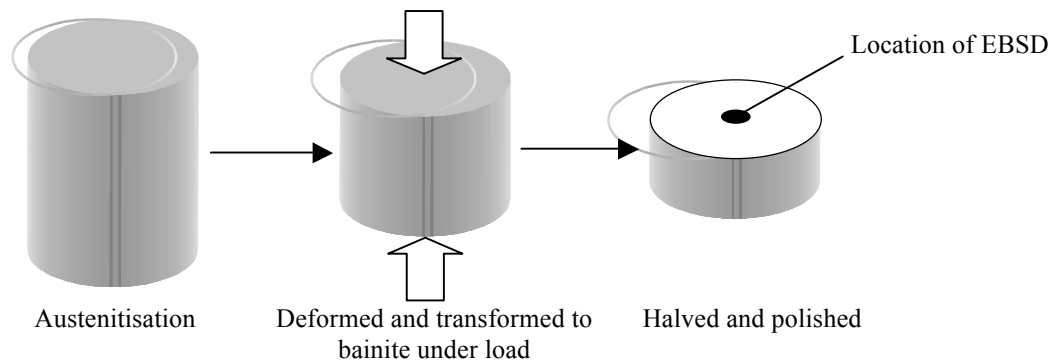
Fig. 3: Location of EBSD on the bainite sample studied in this work.

5- Results and discussion

Statistical approach

Figure 4 shows the parent austenite grains reconstructed from the experimental EBSD map of bainitic grains, as well as the corresponding pole figures for 8 selected grains. The computer program also indexed the bainitic grains in each identified austenitic grain with numbers from 1 to 12. Each indexing number corresponds to a certain variant as defined by Nishiyama–Wasserman orientation relationship. As an example, some of the indexed bainite grains are shown in Figure 5. Finally, the computer program provided the frequency of the operators used in the reconstruction of parent austenite grains, as well as the statistics on the occurrence of all 12 possible variants.

The statistic charts in Figure 6 show that all six operators are present; only operator 2 (misorientation of 19.4° around [100] axis) is less frequent. Such a low frequency has already been observed in un-deformed steels [18] and therefore cannot be attributed to plastic deformation which occurred due to the bainitic transformation. Therefore, it was concluded that the presence of variant selection was unlikely in the sample examined in this work.
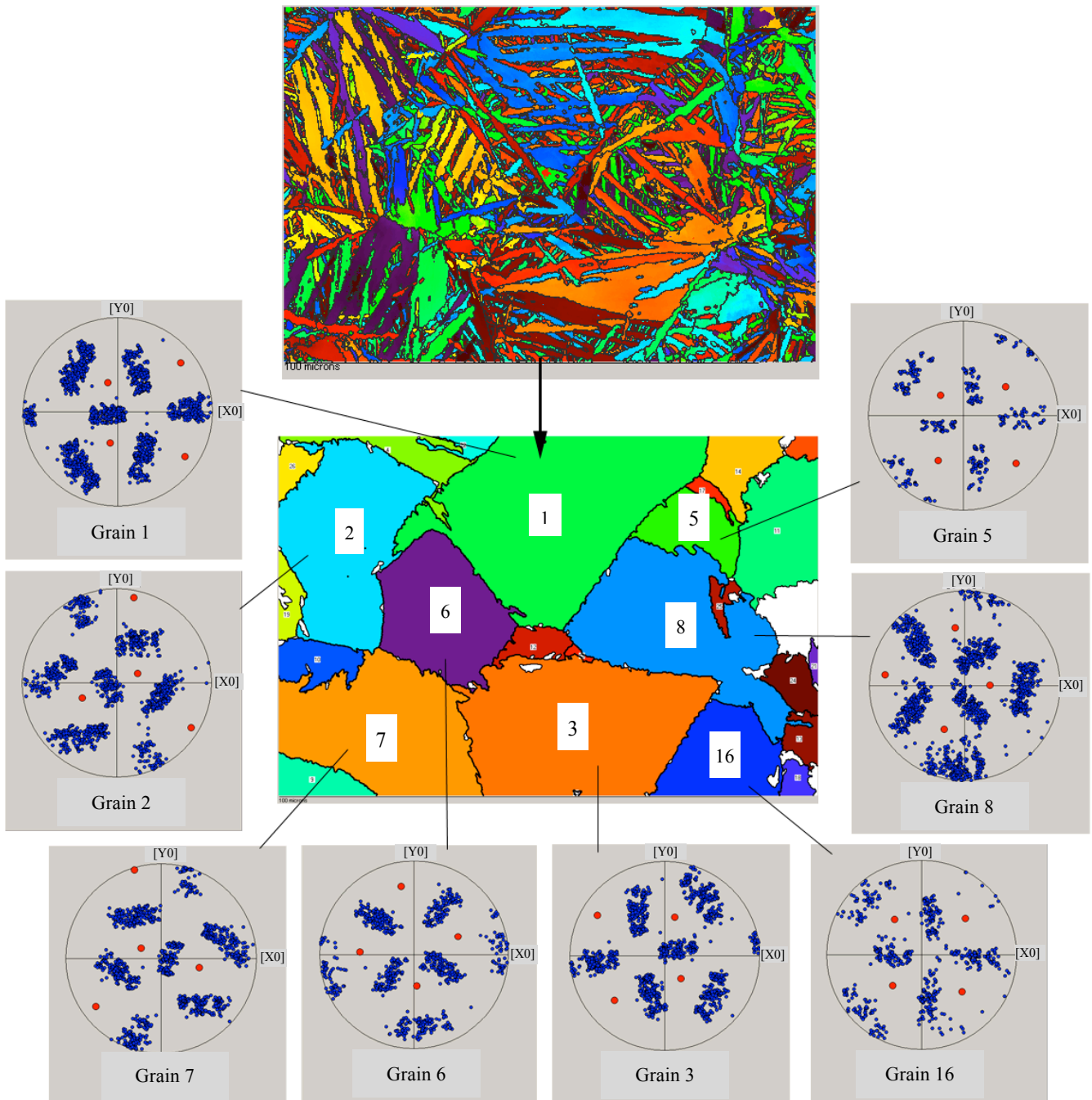
Fig 4: Experimentally acquired EBSD map of bainitic grains (top) and the outcome of ARPGE software which was used to reconstructed austenitic grains (middle). Pole figures of <111> directions shows crystallographic orientations of bainite (blue) and superimposed orientations of the corresponding reconstructed austenite (red).
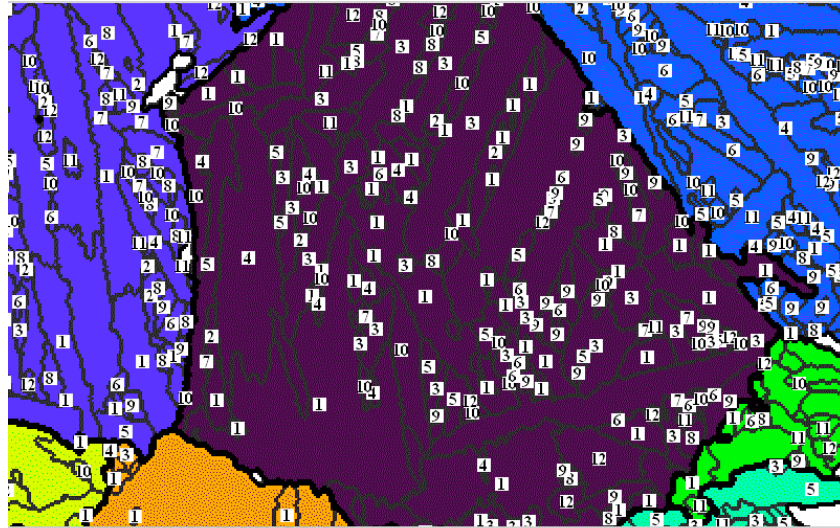
Fig. 5: Variants in each bainitic grains were determined and indexed according to 12 Nishiyama–Wasserman orientation relationship.
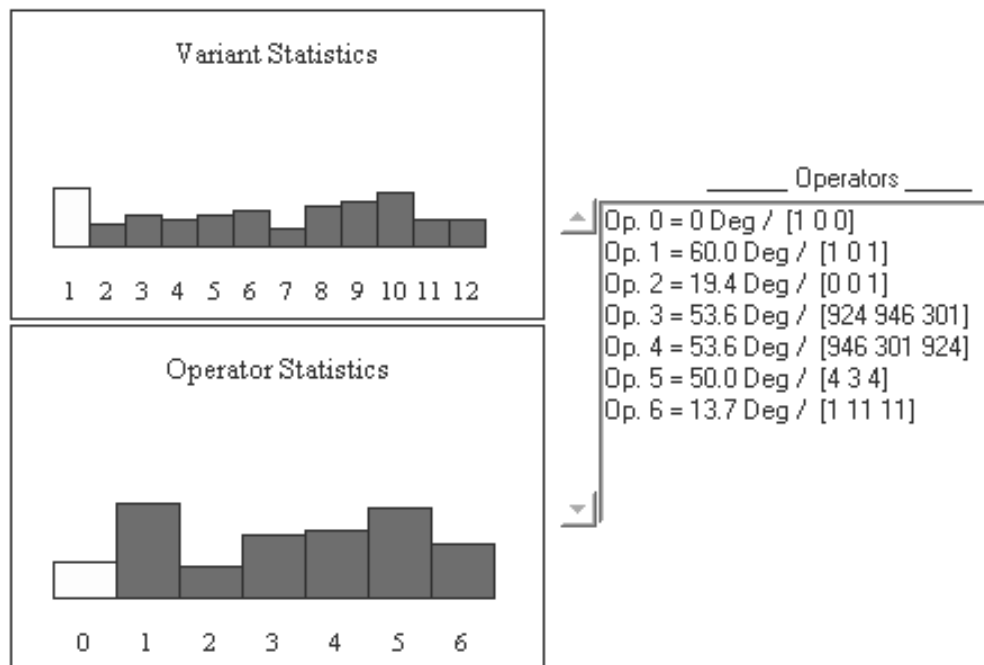

Fig 6: Statistic charts on the variant indexes and operators deduced from the reconstruction of grains shown in Fig. 4.

<u>Micro-texture approach</u>

The crystallographic textures of 4 grains were determined using the experimental data acquired by EBSD method, and demonstrated in form of pole figures. Taking in account the direction of applied load and the crystallographic orientation of parent austenite, the (100) pole figures of the ferrite were calculated for 24 variants. The calculation of pole figures was repeated for 8 variants with the highest positive formation energies. Figure 7 shows the measured and calculated pole figures of the ferrite as well as the measured pole figures of 4 parent austenite grains (*i.e* retained austenite).

Having compared the measured and calculated pole figures of Grains 1, 2 and 4, it was concluded that variant selection did not occur in these grains. This is because all 24 variants are present in the measured pole figures, *i.e.* the 8 variants with the highest positive energies are not prevailing. The measured pole figure of Grain 3 indicates that some variant selection might have occurred in that grain. However, the measured pole figures of Grain 3 do not match with the pole figures of the 8 high-energy variants.

Both approaches used in this work showed that very limited, if any, variant selection has occurred in the bainitic sample which was formed from a plastically deformed parent austenite, despite the presence of an external compressive stress (200 MPa) throughout the phase transformation stage.

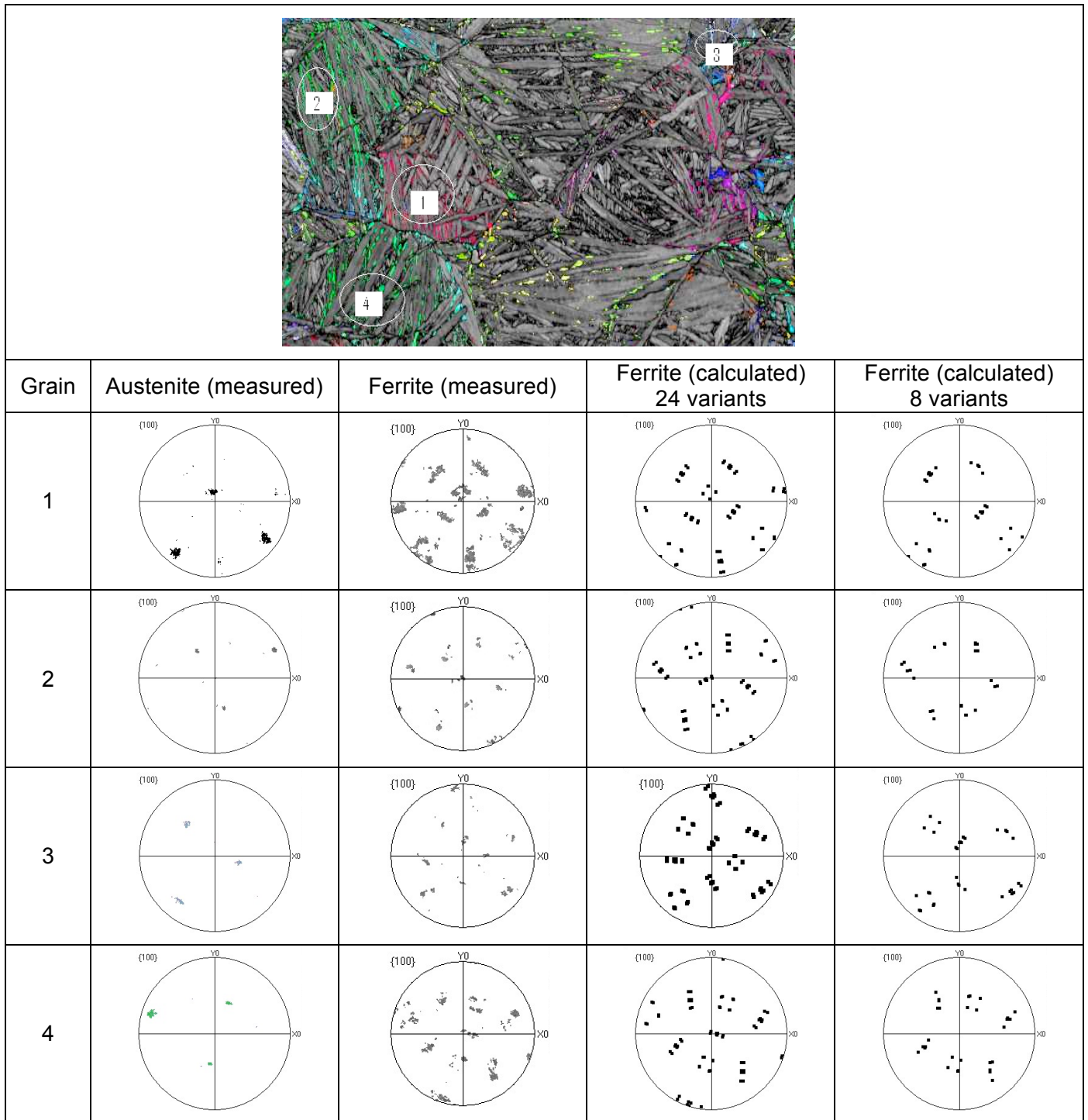| Grain	Austenite (measured)	Ferrite (measured)	Ferrite (calculated) 24 variants	Ferrite (calculated) 8 variants
1				
2				
3				
4				

Fig. 7: Pole figures of 4 grains in a bainitic sample transformed from a plastically deformed austenite under 200 MPa show no strong evidence of variant selection.

6- Conclusions

The combined effect of stress and strain on the crystallographic orientation of bainite was studied using the experimental data (EBSD) and two methodologically different approaches. Given the outcome of this work and results of previous work on the same steel [6,7], it is concluded that the plastic deformation of parent austenite grains suppresses variant selection in the bainitic steel. Also, maintaining an externally applied load during the bainitic transformation does not lead to variant selection. This could be due to uniform distribution, and hence, isotropic nature of the dislocation debris in the deformed grains of the polycrystalline austenite. It must be emphasized that the outcome of this work does not contradict the results reported by Hase *et al.* [6], in which strong variant selections were observed when transforming un-deformed polycrystalline austenite to bainite under an applied load.

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