



Grain orientation statistics of grain-clusters and the propensity of multiple-twinning during grain boundary engineering

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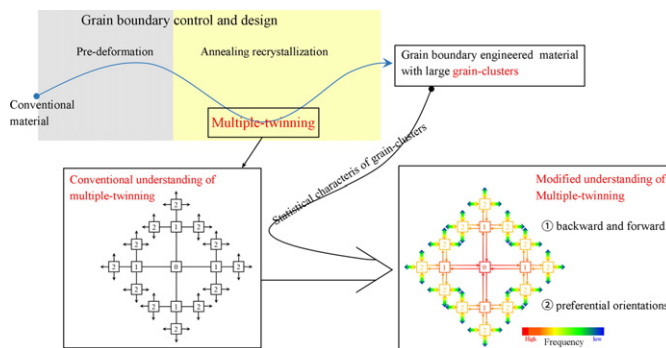
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HIGHLIGHTS

- Dominant orientations were observed to occupy most area and grains in grain-clusters.
- Most mutual misorientations between the dominant orientations in a grain-cluster are of $\Sigma 3$ or $\Sigma 9$ types.
- Multiple-twinning presents back-and-forth pattern to form not only higher but also lower generation twin orientations.
- Preferential orientations exist during multiple-twinning and eventually become the dominant orientations in grain-cluster.

GRAPHICAL ABSTRACT



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ABSTRACT

Large grain-cluster or so-called twin-related domain is a typical characteristic of the grain boundary (GB) engineered microstructure. Grain-cluster is formed via numerous twinning operations starting from single nucleus, and the process is referred to as multiple-twinning. This work investigated the orientation diversity within grain-clusters and the twinning ordering of multiple-twinning based on the statistics of grain-orientations in 30 large-sized grain-clusters from GB-engineered Ni-based alloy 690. The statistics show that the grain-cluster apparently has several dominant orientations. A few dominant orientations occupy most area and most grains in a grain-cluster. Moreover most misorientations between these dominant orientations are of low-order $\Sigma 3^n$ -type ($n = 1, 2$), and the 4 sub-dominant orientations are twinning variants of the first-dominant orientation in most cases. These statistical characteristics of grain-clusters reflect the general behavior of multiple-twinning: back-and-forth pattern and preferential orientations. The twinning operations produce not only higher (forward) but also lower (backward) generation orientations, and the backward probability is higher than the forward. The multiple-twinning shows a propensity to form or access to a few preferential orientations, and results in the formation of dominant orientations of the formed grain-cluster.

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1. Introduction

Twinning is an interesting phenomenon in some materials and can occur during annealing [1–3] or deformation [4], and annealing twin-

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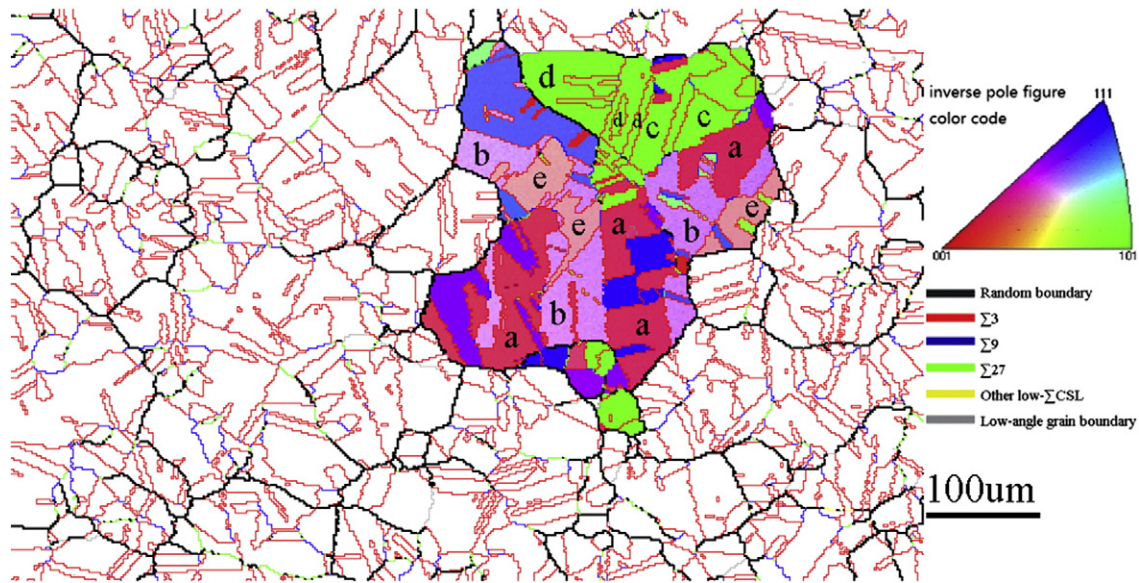


Fig. 1. EBSD map of a GB-engineered alloy 690, in which a grain-cluster was highlighted using the IPF color code. The 5 largest-area orientations in the grain-cluster were designated as a–e in descending order.

boundaries or deformation twin-boundaries are formed, respectively. As a deformation mechanism, twinning has important influence on the mechanical properties of materials [5]. Additionally, the annealing twin-boundaries have special properties, such as stronger resistance to intergranular degradation, compared with random-boundaries [6–8]. Therefore, the twinning can be applied for materials design, and the concept of “grain boundary (GB) engineering” [9–15] was proposed to improve the GB-related properties via “grain boundary control or design” [9].

GB-engineering has been successfully applied to many structural materials, such as austenitic stainless steel [7], Ni-based alloys [11,12], copper and its alloys [13]. After the treatment of GB-engineering, resistance to carbide precipitation [6], impurity segregation, intergranular corrosion [7] and intergranular stress corrosion cracking can be improved resulting from the formation of a great number of special boundaries. The low- Σ CSL boundaries (Σ -value ≤ 29) are generally considered as the special boundaries [16], where the Σ -value denotes the reciprocal density of coinciding sites of two neighboring grains based on the CSL model (coincide site lattice). Twin-boundaries ($\Sigma 3$) and its variants ($\Sigma 3^n$, $n = 2, 3, \dots$) take most fraction of the total special boundaries [17–20]. The proportion of twin-boundaries could be increased to >60% from about 40% by the

treatment of GB-engineering [11,12,17–21], because the face-centered-cubic low stacking-fault-energy metals, such as Ni-based alloys, austenitic stainless steel and brass, are prone to twinning [1,2] in the wake of migrating of the recrystallization front boundaries during annealing. The iterative process of twinning operations starting from a single nucleus is referred to as multiple-twinning [21–25], and the generated annealing twins can be reconstructed as a twinning tree, which is referred to as twin-chain [8,11,22,26,27]. The assembly of all grains in the tree is named grain-cluster or twin-related-domain [8,11,12,24,26]. All inner grains of the grain-cluster have $\Sigma 3^n$ ($n = 1, 2, 3, \dots$) mutual misorientations, and all inner boundaries are types of $\Sigma 3^n$ but outer boundaries are crystallographically random. Large-sized grain-clusters and high proportion of twin-related boundaries are two prominent characteristics of the GB-engineered microstructure [6,10–14,16–18,28–30]. Both of them are the consequences of multiple-twinning [21–25]. So, it is significant to investigate the behavior of multiple-twinning.

A grain may have a great number of twins but four twinning-orientations (variants) at most [25]. It was expected that the probabilities to form any one of the four variants are equal, but no paper confirmed this expectation or existence of preferential variant. The physical process of multiple-twinning is not entirely clear, because it is difficult to observe the process of multiple-twinning in-situ, not mention mapping the grain-orientations simultaneously. Generally we study the multiple-twinning by statistical analysis of grain-clusters. Mason et al. [31] found that the distribution of the number of grains per grain-clusters can be fit to Weibull distribution. Cayron [24] got similar results about the grain number distribution. Meanwhile the lengths of the longest twin-chain in the grain-clusters were calculated in Ref. [24]. The number of grains in a grain-cluster corresponds to the number of twinning operations of the multiple-twinning to form the grain-cluster. Therefore, the potential number of twinning-operations per multiple-twinning is fit to the Weibull distribution. During recrystallization, a few nuclei perform multiple-twinning extensively but most nuclei just perform a few iterations of twinning.

Apart from the number of grains, the number of orientations is another significant parameter for grain-cluster statistics. Some grains may have the same orientation in a grain-cluster, and thus the number of orientations is less than the number of grains. In addition, the number of grains per orientation in a grain-cluster should be considered as well. The three parameters, i.e. the number of grains, the number of orientations and the numbers of grains per orientation in a grain-cluster, would synthetically reflect the physical

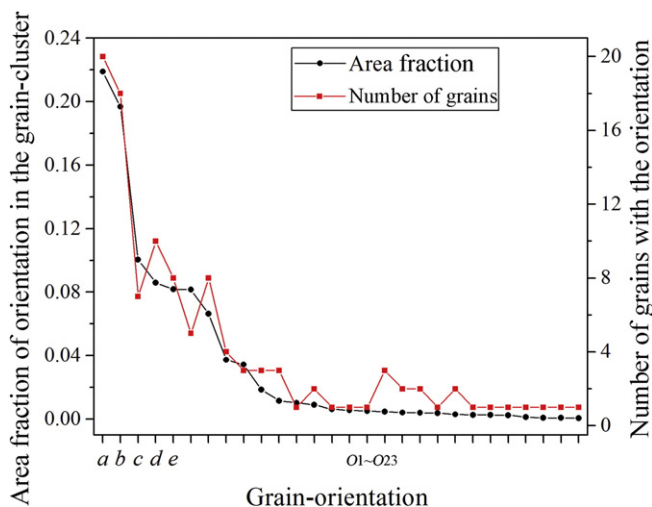


Fig. 2. Distributions of the area fractions and the numbers of grains per orientation in the grain-cluster highlighted in Fig. 1.

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