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Twinning Accommodation in Highly Aligned Superconducting $YBa_2Cu_3O_{7-x}$*

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Abstract

Defects in the form of twins, slips, kinks and cracks have been studied at room temperature by transmission electron microscopy. In highly aligned $YBa_2Cu_3O_{7-x}$, multiple twinning can be observed, where the orientation of twin planes is varied by accommodation by slipping and kinking. Suitable $\langle\bar{1}10\rangle\{110\}$ slip systems are able to occur in this material. Formation of cracks on subgrain boundaries may occur after twinning in order to relieve transformational and thermal stresses.

1. Introduction

Recently, there has been considerable interest in superconducting $YBa_2Cu_3O_{7-x}$ {123} owing to the high critical current density J_c of $\sim 10^5\ \mathrm{A\,cm^{-2}}$ for bulk materials both in zero field and in high magnetic field (Chu 1989). The fabrication technology of {123} has been under continuous improvement since the first highly aligned {123} was initially made by the partial melting technique (Jin *et al.* 1989). The key feature is that crystal growth should occur in a high-viscosity liquid phase that simulates a glass phase. The liquid phase (principally a Cu-rich phase) serves as both a flux and as a component of the precipitated crystal. The crystals exhibit a preferred crystal habit plane (001) (Schneemeyer *et al.* 1987; Nakahara *et al.* 1987) and, as such, provide the necessary condition for aligned crystal growth. With changes in processing, however, the defects in the material proportionally change because all defects are related to the crystalline and transformational conditions. In highly aligned {123}, twins, kinks and cracks have been studied by transmission electron microscopy (TEM) because defects may be detrimental to the properties of the material and they may be important for flux pinning (Zhou *et al.* 1989*a*).

2. Experimental Procedure

The specimens were made by partial melting at ~1000°C for a short time (~30 min.) and then sintering at ~930°C for greater than 6 h in order to make highly aligned polycrystals. Details of these methods have been published

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elsewhere (Zhou *et al.* 1989*b*). Microstructural and compositional studies were performed on ion-milled foils with a JEOL JEM-2000FX electron microscope equipped with a Link Systems energy-dispersive spectrometer.

3. Results and Discussion

As is well known, the formation of twins is due mainly to transformation stresses that occur when the {123} structure changes from tetragonal to orthorhombic upon cooling (Zhou *et al.* 1989*a*). These stresses can be accommodated or relieved by multiple twinning, slipping and/or kinking in aligned {123}.

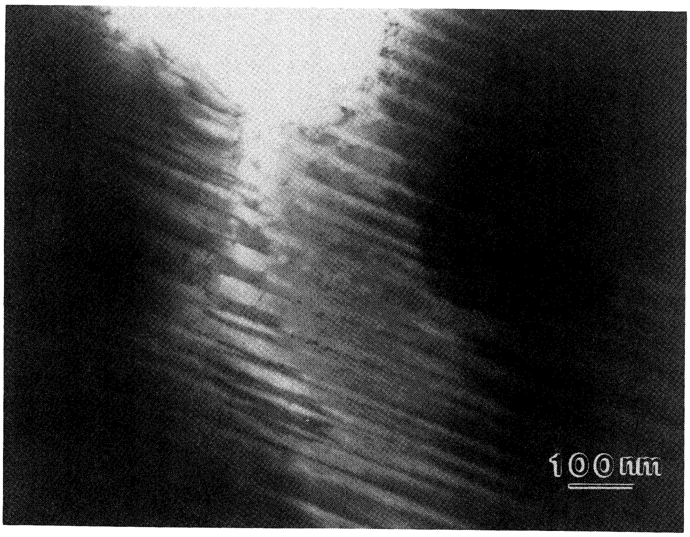

Fig. 1. Image of multiple twinning in aligned {123}.

Fig. 1 shows a uniformly aligned twinning structure between subgrain boundaries. It is possible to follow the twins connected in this way through a large number of subgrains, and as many as 30 have been counted. Multiple twinning is highlighted in this material by a number of {110} twinning systems.

Fig. 2 shows that the twinning shear is accommodated by slip. As seen in Fig. 2*a*, the slip bands are clearly placed on the basal plane and are nearly perpendicular to the surrounding twin lines (actually twin planes). In this case, twin planes cross from one grain to a neighbouring subgrain with little change in orientation. In Fig. 2*a*, the displacement of twin planes after slipping is very small, ~200 nm, which is half of a fringe spacing, and the displacement depends on the movement of the dislocations. Presumably, the slipping or twinning shear occurs on suitable $\langle\bar{1}10\rangle$ {110} systems, as shown in Fig. 2*b*. This is similar to slip systems in a number of materials, including austenite (Porter and Eastering 1981). As can be seen, the twin plane vector is [110] and the slip vectors on the interface are $[\bar{1}10]$ and $[\bar{1}\bar{1}0]$. After slipping, the twin plane has become a glissile boundary, where the glide planes are parallel. If the interface dislocations have a Burgers vector that is defined in either twin

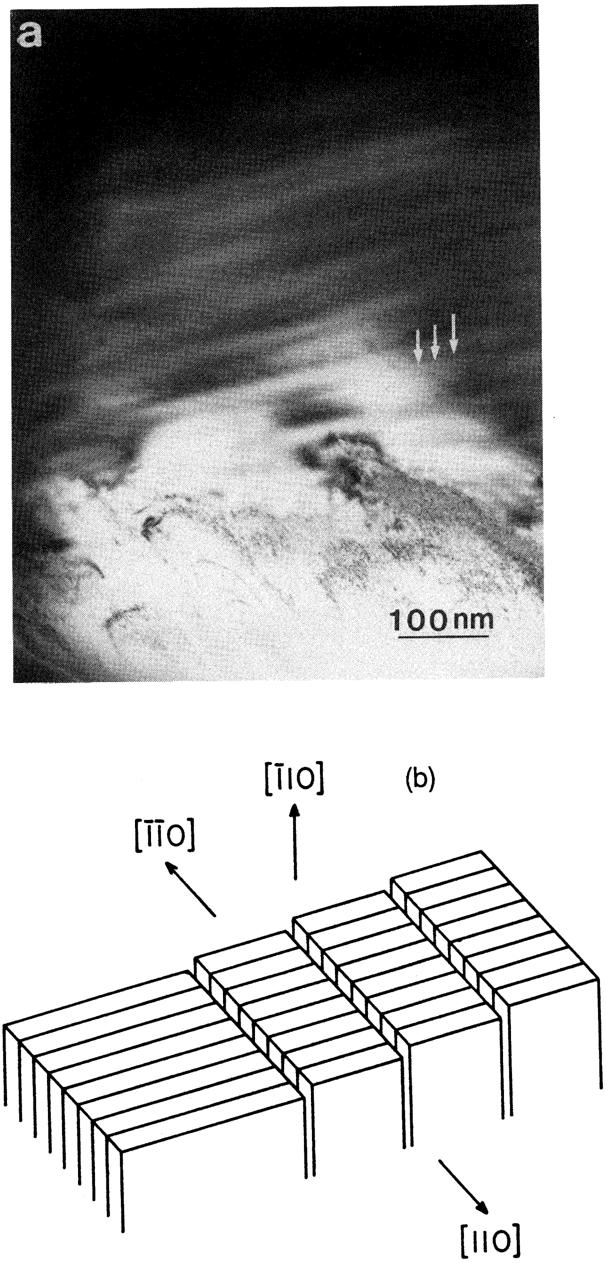

Fig. 2. (*a*) Image of accommodation of twinning shear through slipping. Arrows show slip bands. (*b*) Schematic diagram of twinning shear through slip to change orientation of twin planes.

lattice or the dislocations are pure screw, then the interface will be glissile and the movement of these dislocations accomplishes the simple shear. Thus, the lattice structure is not deformed (Christian 1975; Wayman 1970).

If a slip plane in one subgrain is misaligned with the twin plane in an adjacent subgrain, the lattice in the second subgrain can kink or bend to

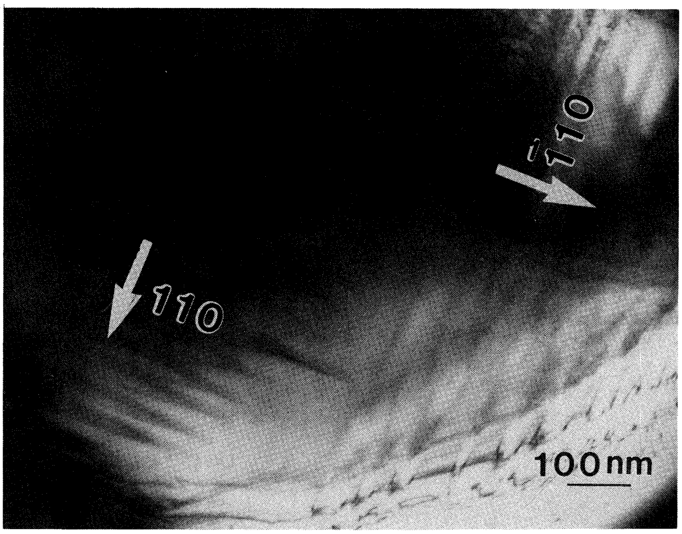

Fig. 3. Image of accommodation of twinning shear through kinking. Arrows show direction of twin planes.

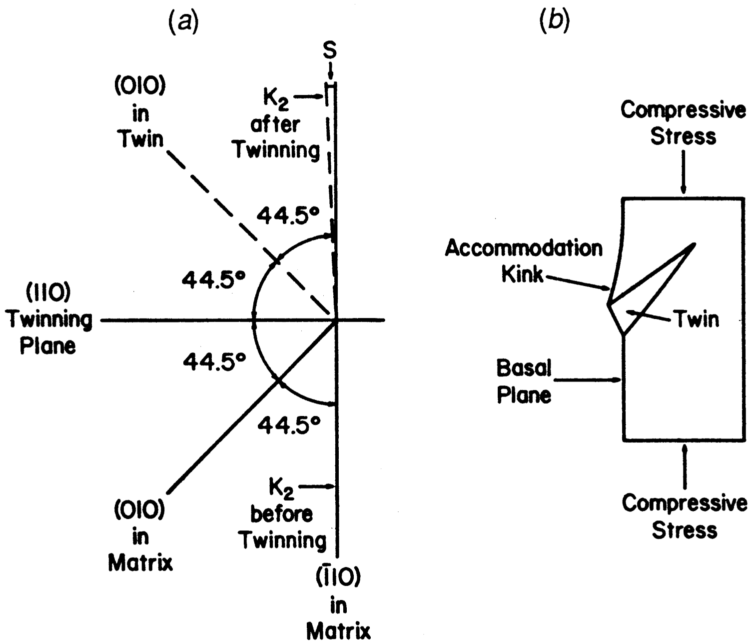

Fig. 4. Schematic diagram of twinning shear in aligned {123} showing: (*a*) position change of {110} twin plane K_2 before twinning and after twinning; (*b*) surface tilt and accommodation kinks resulting from intersection of half-lens twin with surface.

accommodate the twinning shear, as shown in Fig. 3. It can be seen that the twins on two neighbouring subgrains are nearly perpendicular to one another. This leads to a distortion or rotation of the superconducting microstructure when the twin planes on aligned grains are aligned with each other. Fig. 3

shows how the twin planes are rotated and oriented between neighbouring grains. An explanation of the kinking mechanism in twinning shear has been published elsewhere (Zhou *et al.* 1989*a*). According to this model, kinking can be explained in terms of the diagram shown in Fig. 4*a* which illustrates how the angle between the two {110} planes changes from 90 to 90–S degrees, where $S = 0{\cdot}97°$ (Zou *et al.* 1988) or $0{\cdot}89°$ (Sarikaya *et al.* 1988). After twinning shear, symmetry conditions require the twin plane K_2 to rotate anticlockwise in the {123} crystal. This causes a contraction in the twinned crystal parallel to the basal plane, as shown in Fig. 4*b*. Here, the basal plane in the crystal adjacent to the half-lens of the twin is bent or kinked in order to allow the parent lattice to accommodate the shear strain of the twin.

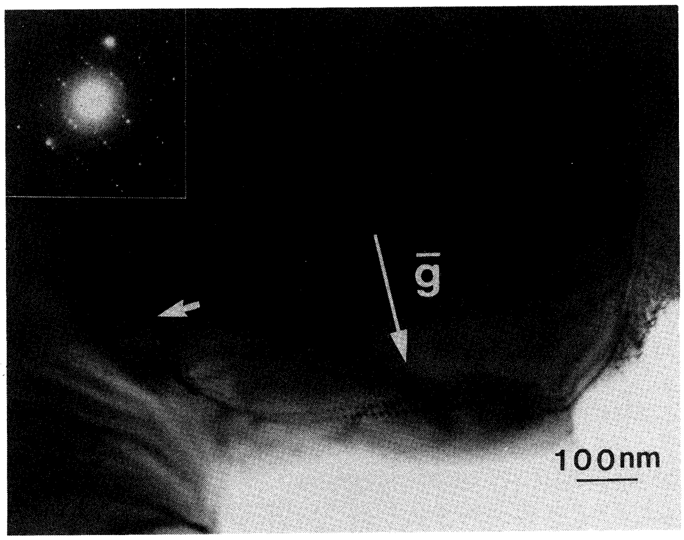

Fig. 5. Image of low-angle subgrain boundary with Moiré fringes and crack. Arrows show the direction of diffraction vector ***g*** and crack.

It is interesting to observe not only images of the twinning structure but also images of the interface on the subgrain boundaries. For a low-angle subgrain boundary, Moiré patterns can be seen, as shown in Fig. 5. The direction of the Moiré fringes deviates slightly from the direction of the diffraction vector ***g***. Further, the spacing of the Moiré fringes appears to be constant. It can be seen that the orientation and slope of the subgrain boundary does not change. This result is consistent with that of lattice fringes, where a very small intersecting angle (<1°) between subgrains has been observed (Zhou *et al.* 1989*a*). In Fig. 5, a crack is observed along the subgrain boundary. Bend contours disappear and stresses on the subgrain boundary are relieved after formation of cracks.

In conclusion, accommodation of transformational and thermal stresses has been demonstrated in highly aligned {123} by twins, slips, kinks and cracks. Suitable $\langle\bar{1}10\rangle$ {110} slip systems can occur in {123}. The formation of cracks on subgrain boundaries may follow twinning shear. In addition, stresses may result from remanent flux and lead to cracks.

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