Development of Sharp \{011\}(211) Textured Silver Substrate for Superconducting Tapes

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Texture formation in pure silver was investigated in order to obtain sharply Brass \{011\}(211) type textured silver sheet that can be used as a substrate for Y-123 superconducting coated tapes without any buffer layers. The feature of recrystallization texture after the two-step annealing appeared as two peaks close to Goss \{011\}(100) orientation and Brass \{011\}(211) orientation respectively with other weak components along c-fiber in specimens rolled at room temperature, and only one peak close to Brass \{011\}(211) orientation with weak components limited to cube orientation, rotated cube orientation and orientation close to Copper \{112\}(111) orientation in those warm rolled at 150°C. By using the improved metallurgical processing, a very sharp Brass \{011\}(211) type texture has been successfully realized in specimen, which was cast in vacuum, warm rolled by 92% at 150°C and subsequently annealed as 200°C-20min + 800°C-180min in nitrogen. There are some critical conditions on the formation of sharp Brass \{011\}(211) type recrystallization texture: a low oxygen content in the starting material, elevated rolling temperature, and the selection of lower primary recrystallization temperature of two-step annealing process.

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1. Introduction

Since the discovery of high-temperature superconductivity in cuprate materials, world-wide efforts have been focused on research and development of making wires or tapes of HTS (high-temperature superconductor) with high \(J_c\) (critical current density). However, two intrinsic material problems, i.e., weak intragrain pinning and weak intergrain coupling, have slowed down the progress towards fabricating these materials into useful form with acceptable superconducting properties. The origin of weak intragrain pinning is structural in nature and can be overcome by chemical substitution and incorporation of defects. Early studies show that the high-angle grain boundaries acting as Josephson coupled weak links are the origin of degradation in \(J_c\) of polycrystalline material compared to that of single crystal. It is likely that the variation in \(J_c\) with grain boundary misorientation is similar in the mostly studied superconducting compounds such as TI-1223, Hg-1223 and Y-123. Accordingly, the control of grain boundary misorientation to achieve low-angle grain boundaries distribution is a very important procedure in fabricating HTS with high \(J_c\).

Among the many techniques on overcoming the grain boundary weak link problem, such as IBAD (ion beam-assisted deposition), PLD (pulsed laser deposition) and RABITS (rolling-assisted—biaxially textured substrates) of thin film route, LPE (liquid phase epitaxy) and spray pyrolysis of thick film route, there is a common issue of how to achieve a sharp silver texture of the correct form considering the basic substrate property requirements as flexibility, texture, similar thermal expansion coefficient to the superconducting phase, lattice-matching, chemical compatibility, and limited oxidation at processing temperatures.\(^1\)

Due to its low SFE (stacking fault energy), the particular characteristic of silver is that its textures, as both deformed and recrystallized states, are quite different from those of regular f.c.c. (face-centered-cubic) metals, such as aluminum, nickel and copper. Therefore, it is considerably more difficult to get single sharp texture in silver. After Hu’s early study on the texture transition in pure silver, many recent research works have been concentrated mainly on achieving single orientation in the texture of silver substrate.\(^2\)–\(^10\) An advanced sharply cube-textured silver substrate was successfully obtained by simple warm rolling and subsequently annealing in our previous work.\(^11\) All those endeavors have promoted the possibility for silver substrate to be used in high-temperature superconductors. Although the cube-textured \{001\}(100) silver has been widely used in the attempt of making TI-1223 and Nd-123 films, its drawback of generally giving two biaxial orientations often introduces high-angle grain boundaries acting as weak links in making the most popular high-\(T_c\) superconducting Y-123 film.\(^12\)–\(^16\)

The present understanding suggests that \{011\} textured silver is most suitable as a substrate for obtaining the biaxially aligned Y-123 among various textures of silver.\(^9\) Rotated Goss \{011\}(011) type textured silver tape has been successfully used to get biaxially aligned Y-123.\(^17\) Brass \{011\}(211) type textured silver substrate has also been tried in making Y-123 film, but the texture was neither sharp nor stable.\(^18\)–\(^19\) Suo et al. have proposed an optimized method to get pure and stable \{011\}(211) textured silver ribbon with long length and the model on the formation of Brass \{011\}(211) texture in silver explained by twinning mechanism.\(^17\) Following this, Doi et al. reported their work on making Brass \{011\}(211) type textured silver tape.\(^13\) In our work on warm rolling and subsequent annealing in silver, a very sharp Brass \{011\}(211) type texture with high intensity in ODF but with trace of other components was obtained. The metallurgical processing will be detailed in this paper.

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2. Experimental Procedure

Silver ingots of commercial purity were obtained by casting in vacuum. After homogenization at 600°C for 2 hours in nitrogen, pre-rolling in reduction in thickness at about 40% and annealing with 500°C–60 min were carried out to get random samples. Final rolling was conducted at room temperature and 150°C. For warm rolling, the silver sheet was pre-heated to the desired temperature in oil bath before each pass. Hence it is considered that the exact temperature of rolling was likely subjected to some decreases. At corresponding reductions in thickness of 80%, 92%, 95% and 99% on rolling, samples were cut off and then annealed in nitrogen for recrystallization, followed by slow cooling.

The X-ray incomplete pole figures of those deformed and annealed specimens were then measured by means of the back reflection method with filtered Cu-Kα radiation to a maximum tilt angle α = 75°. From three measured incomplete pole figures ([111], [100] and [110]), the recalculated pole figures and reliable orientation distribution functions (ODFs) were calculated using the iterative series expansion method, which has been originally proposed by Dahms and Bunge20,21) and modified by Inoue et al.22)

3. Experimental Results and Discussion

3.1 Rolling texture

The deformation texture feature of 150°C warm rolled silver sheet was reported in our previous work.11) The deformation texture feature of 150°C warm rolled silver sheet was reported in our previous work.11) The warm rolling textures commonly obtained in silver sheet were reported in our previous work.11) The warm rolling textures of specimen cast in vacuum and rolled at room temperature consist of Brass [011](211), Copper [110](111), S [123](412) and cube [001](100) components and the shifts from ideal position with the increase of rolling reduction in thickness could be observed. A considerable intensity of cube component was observed due to the extensive partial recrystallization occurring during rolling at elevated temperature.

The rolling textures commonly obtained in silver sheet rolled at room temperature consist of Brass [011](211) orientation and Goss [011](100) orientation. Figure 1 shows φ₂ = 0° and φ₂ = 45° ODF sections and [111] pole figure of deformation texture of specimen cast in vacuum and rolled at room temperature to 95% reduction in thickness. In this figure, Bunge’s notation for the Euler angles is employed. It can be seen that the texture is [111](12, 5, 5) orientation with weak Goss [011](100) component.

3.2 Recrystallization texture

A strong cube [001](100) type texture was achieved by warm rolling and subsequent annealing in our previous work.13) It is stable at 700°C. However, the texture turned to strong [011](533) type with trace of cube [001](100) orientation after additional annealing 850°C–480 min in specimen, which was cast in air, warm rolled by 95% at 150°C and subsequently annealed as 150°C–10 min + 500°C–30 min + 850°C–480 min. As presented in Fig. 2 of φ₂ = 0° and φ₂ = 45° ODF sections and {111} pole figure of this recrystallization texture, the maximum intensities in ODF and pole figure are 41.82 and 9.21 respectively. Doi et al. reported a Brass [011](211) type textured silver tape made by cold rolling and annealing 850°C–600 min in argon.13) It was suggested in the work of Suo et al. that a first stage of fast temperature ramp up to 500°C would help the grain growth in [011](211) orientation during the second stage of high temperature annealing.7) Therefore, two-step annealing processes of 500°C–30 min + 850°C–300 min and 500°C–30 min + 850°C–480 min were initially employed on specimens rolled at room temperature and 150°C in this study.

Figure 3 shows the φ₂ = 0° and φ₂ = 45° ODF sections and [111] pole figure of recrystallization texture after two-step annealing 500°C–30 min + 850°C–300 min in specimens cast in vacuum. For the specimen rolled by 95% at room temperature, the texture component is Brass [011](211) orientation with weak [011](499) component. For the specimen warm rolled by 95% at 150°C, the texture component is [011](533) orientation with weak cube [001](100), [029](092) (WTD-cube orientation rotated around transverse direction) and [5, 5, 11](11, 11, 10) components. As indicated in Fig. 4 of the φ₂ = 0° and φ₂ = 45° ODF sections and [111] pole figure of recrystallization texture after two-step annealing 500°C–30 min + 850°C–480 min in specimens cast in vacuum, where the annealing time of second step was prolonged to 480 minutes, Goss [011](100) component appeared with Brass [011](211) orientation as majority and [011](477) orientation as minority in specimen rolled by
95% at room temperature while texture components were simplified as main component of $\{011\}(533)$ and minor component of $\{029\}(092)$ in specimen warm rolled by 95% at 150°C. It should be pointed out that the intensities in ODFs and pole figures increased remarkably after extending high temperature annealing.

3.3 Discussion on texture formation

The recrystallization textures in silver shown above were definitely influenced by the impurity content, in particular oxygen content, rolling condition and annealing procedure. Actually, a pretty sharp and pure Y $\{111\}$ type recrystallization texture, which is often observed in deformed b.c.c. (body-centered-cubic) materials, was obtained in specimen, which was cast in air, warm rolled by 92% at 150°C and subsequently annealed as 150°C–10 min + 500°C–30 min + 850°C–480 min (shown in Fig. 5). For the specimens cast in vacuum, warm rolled and subsequently annealed according to the two-step annealing processes in last section, their recrystallization texture feature of one strong peak close to Brass $\{011\}(211)$ orientation along $\alpha$-fiber with some weak components was always preserved no matter what kind of reduction in thickness was selected from 80%, 92%, 95% and 99%. An example of 95% warm rolled specimen has been shown in Fig. 3(b) and Fig. 4(b). It can be suggested that the Brass $\{011\}(211)$ type texture could be obtained in a wide range of reduction in thickness in warm rolled specimens if the oxygen content was reduced by the utilizing of improved casting method.

Rolling texture has a significant effect on the formation of recrystallization texture. There are two totally different
patterns of recrystallization texture that can be detected after the two-step annealing processes of 500°C–30 min + 850°C–300 min and 500°C–30 min + 850°C–480 min in specimens rolled at room temperature and those warm rolled at 150°C. For the former, the recrystallization texture feature appeared as two peaks close to Goss (011) orientation and Brass (011)(211) orientation respectively with other weak components along α-fiber. The intensities of these two peaks changed with the reductions in thickness applied, and in some cases the intensity of the peak close to Goss (011)(100) orientation was even higher than that of the peak close to Brass (011)(211) orientation. For the latter, only one peak close to Brass (011)(211) position can be found under any reduction in thickness, and the weak components were limited to cube orientation, rotated cube orientation and orientation close to Copper (112)(111) position, all of which did not belong to α-fiber. These results can be partly attributed to the origin of their rolling textures as shown in Fig. 1 and in our previous work.

4. Improved Metallurgical Processing to Obtain Single (011)(211) Brass Orientation Texture in Silver Substrate

The mechanism of stable (011) recrystallization texture formation was supposed to be a selective grain growth in which the [011] grains nucleate during the primary recrystallization and grow preferentially by consuming other orientated grains due to their preponderant grain boundary mobility.23 In other words, a secondary recrystallization process is responsible for the formation of strong Brass (011)(211) orientated grains. Therefore, one of the key procedures for achieving a sharp Brass (011)(211) type texture is the control of the nucleation of [011] grains, which are likely to grow along [211] direction during the high temperature annealing. However, as discussed in the front part no satisfying experimental result of recrystallization texture was obtained after two-step annealing processes of 500°C–30 min + 850°C–300 min and 500°C–30 min + 850°C–480 min. It has been pointed out in the work by Hu et al. that complete recrystallization has almost fully taken place after annealing at 200°C in deformed silver specimen.4) This has also been confirmed in our previous work on warm rolled and subsequent annealed silver sheet. Therefore, we believe that a lower first step annealing temperature around 200°C is more reasonable to be used in the two-step annealing process to get appropriate secondary recrystallization nuclei. Accordingly, an improved metallurgical processing of two-step annealing 200°C–20 min + 800°C–180 min was suggested in this study.
As shown in Fig. 6 of the $\varphi_2 = 0^\circ$ and $\varphi_2 = 45^\circ$ ODF sections and {111} pole figure of recrystallization texture after two-step annealing 200°C–20 min + 800°C–180 min, {011}(522) orientation in specimen rolled by 95% at room temperature and {011}(533) orientation with weak Copper {112}(111) component in specimen warm rolled by 95% at 150°C are obtained respectively. Although only one peak is obtained in the specimen rolled by 95% at room temperature, strong $\alpha$-fiber with more than one peak was obtained in specimens under other rolling reductions in thickness. On the other hand, a main peak close to Brass orientation with weak components limited to TD-rotated cube orientation and orientation close to Copper {112}(111) position was found in warm rolled specimens under other rolling reductions in thickness. A very sharp {011}(955) texture with maximum intensities of 62.43 in ODFs and 15.22 in pole figure, which is only three degrees rotation around normal direction from exact Brass {011}(211) position, was realized in specimen cast in vacuum, warm rolled by 95% at 150°C and subsequently annealed as 200°C–20 min + 800°C–180 min. These results are demonstrated in Fig. 7 and Fig. 8. Compared to the result by Suo et al., the Brass {011}(211) type recrystallization texture obtained by our improved metallurgical processing are much more simple. Only trace of {2, 2, 11}(1, 10, 2) orientation can be detected when the ODF and pole figures are plotted with lower contour levels. It is worth to point out that the fact that the only one strong peak very close to exact Brass {011}(211) position can be achieved in a wide range of rolling reduction in thickness under improved metallurgical processing indicates the feasibility and reliability of this method of making Brass {011}(211) type textured silver substrate for superconducting tapes.

5. Conclusions

A practical way of making sharply Brass {011}(211) type textured silver substrate for superconducting tapes by means of warm rolling and subsequent improved two-step annealing has been presented in this study. It has been confirmed by the experimental facts that the Brass {011}(211) type recrystallization texture development of pure silver was significantly affected by the rolling temperature, impurity content, especially oxygen content, and the selection of primary annealing temperature. By using the improved metallurgical processing, a very sharp Brass type texture has been successfully obtained in a specimen which was cast in vacuum, warm rolled by 92% at 150°C and subsequently annealed for 20 minutes at 200°C and for 180 minutes at 800°C in nitrogen. As the sharp Brass {011}(211) type texture can be realized in a wide range of rolling reduction in thickness, this new technology presents a more promising way in developing single Brass {011}(211) type textured metallic substrates which are highly favorable for wires or tapes of high temperature superconductors.

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