J Mater Sci (2010) 45:3514–3519
DOI 10.1007/s10853-010-4392-9

The influence of electroplastic rolling on the mechanical deformation and phase evolution of Bi-2223/Ag tapes

Yongjin Lu · Timing Qu · Pan Zeng · Liping Lei · Gang Fang · Jianfeng Sun

Received: 5 November 2009 / Accepted: 6 March 2010 / Published online: 23 March 2010

Abstract Electroplastic rolling (EPR) of Bi-2223/Ag superconducting wires was performed, where pulse currents were applied during rolling to introduce an electroplastic effect. It was found that the rolling force decreased significantly compared with the traditional rolling process. Furthermore, EPR favorably minimized the sausage effect. It is revealed that the electroplastic effect can facilitate the mechanical deformation of Bi-2223/Ag composites. Segments of the Bi-2223/Ag tapes were heat treated at 830 °C for different time periods. The phase assemblies of these samples suggest that current pulses contribute to faster transformation kinetics from the Bi-2212 phase to the Bi-2223 phase. In addition, a preliminary improvement of 28% of critical current density has been achieved in a fully processed tape with EPR.

Introduction

At present, silver-sheathed (Bi, Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_x$ (Bi-2223/Ag) superconducting tapes can be mainly fabricated using the standard powder-in-tube (PIT) technique. The technique involves a series of mechanical deformation and thermal treatment steps. The objective of mechanical processing for Bi-2223/Ag tapes is to obtain homogeneity and a high density of the superconducting powder, and to form strong *c*-axis texture. Subsequent heat treatment mainly achieves phase transformation from Bi-2212 to Bi-2223, stronger connectivity between the Bi-2223 grains, and crack healing [1]. Great progress has been made in improving the performance of the finished superconducting tapes for large-scale applications. In particular, the critical current (I_c) for the finished tape increases to over 200 A using the overpressure sintering technique [2, 3]. However, the critical current density (J_c) remains far lower than those in single crystals and epitaxial films [4, 5].

The performance of multifilament superconducting tape is limited because of difficulties in manufacturing a composite wire from three dissimilar materials and in controlling the uniformity and density of ceramic cores. Consequently, refining plastic deformation is one of the techniques used to enhance the capability for current conduction in Bi-2223/Ag tapes. In order to optimize the processing of composite wires, Grivel [6] showed that Bi-2223/Ag tapes using nickel in the place of silver alloy can obtain higher mechanical strength and critical current density, but this method is not sufficiently advanced to be applied to multifilamentary tapes. Hušek and Kováč [7] performed a detailed study and found that two-axial rolling from a wire to the tape can enhance the filling factor and filament homogeneity of the tape. Bay and Nielsen [8] successfully fabricated a tape from square wire with remarkable improvements in homogeneity and critical current. It is apparent that refinements in mechanical processing were accompanied by additional mechanical constraints. However, compared to conventional processing, manufacturing the tools becomes the main barrier to commercial production, and the techniques increase the complexity and uncontrollability of the high performance tapes.

Y. Lu (✉) · T. Qu · P. Zeng · L. Lei · G. Fang
Key Laboratory for Advanced Materials Processing Technology, Ministry of Education, Tsinghua University, Beijing 100084, China
e-mail: luyj06@mails.tsinghua.edu.cn

Y. Lu · T. Qu · P. Zeng · L. Lei · G. Fang
Department of Mechanical Engineering, Tsinghua University, Beijing 100084, China

J. Sun
Innova Superconductor Technology Co. Ltd. (INNOST),
Beijing 100176, China

Since 1963, Troitskii and many other researchers have devoted much energy to investigate the plasticity of metals and alloys applying current pulses through test materials. The common phenomenon called the electroplastic effect was confirmed by a series of experiments. This effect can enhance the deformability of metallic materials because of an improvement in the active mobility of dislocations stimulated by electropulsing [9–12]. However, there are no open publications describing the electroplastic process of Bi-2223/Ag wires. In this study, electroplastic rolling (EPR) of Bi-2223/Ag wires was applied during manufacturing, and the first heat treatment using different durations was carried out for short tapes. This allowed for the investigation of the influence of current pulses on the mechanical deformation, the phase evolution, and the critical current density of Bi-2223/Ag tapes.

Experimental details

Bi-2223/Ag wires of 1.7 mm in diameter were made using the standard PIT method described by INNOST, using a precursor powder with the nominal composition of $Bi_{1.8}Pb_{0.33}Sr_{1.87}Ca_{2.0}Cu_{3.0}O_y$. The EPR processes were conducted on a specially designed rolling system, including conventional rolling equipment, a pulse trigger, and an electric pulse measurement system. A schematic illustration of the experimental arrangement used for the electroplastic studies is presented in Fig. 1. The pulse current is applied to the wire by a sliding contact between the conducting wheel and the upper roller, and the current direction is the same as the rolling direction. Traditional rolling (TR) can also be performed by shutting off the power. In this research, the diameter of the roller used was 60 mm, and the rolling speed was 2 m/min. The pulse trigger generated current pulses from 100 to 200 Hz with a current density of about 10^3 A/mm^2 with a pulse duration of about 60 μs. The discharge voltages are monitored with an oscilloscope, and the calculation of pulse current is based on the Hall Effect. In addition, the rolling force can be continuously recorded using a stress sensor connected to the upper roller.

Three different rolling methods were used. The detailed procedures are shown in Fig. 2. For EPR_3P samples, the wire was first deformed to a tape of 0.24 mm in thickness through two passes of EPR, and then a normal flat rolling. For comparison, TR_3P samples were produced by three passes of normal flat rolling with a degree of deformation

Fig. 1 Schematic diagram of the EPR system

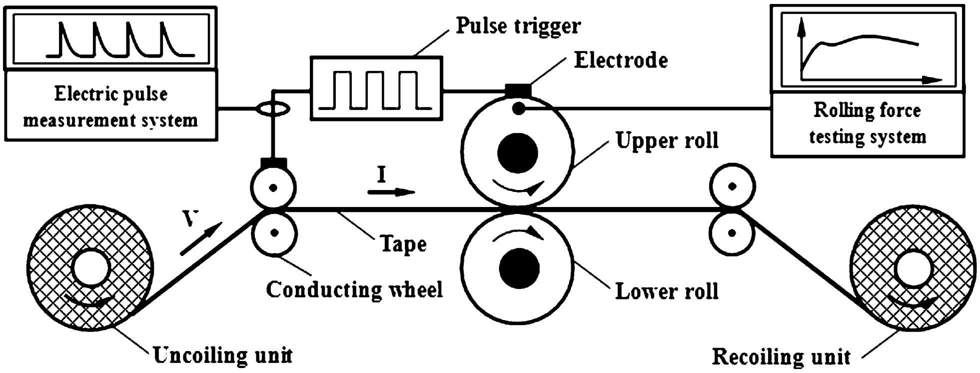
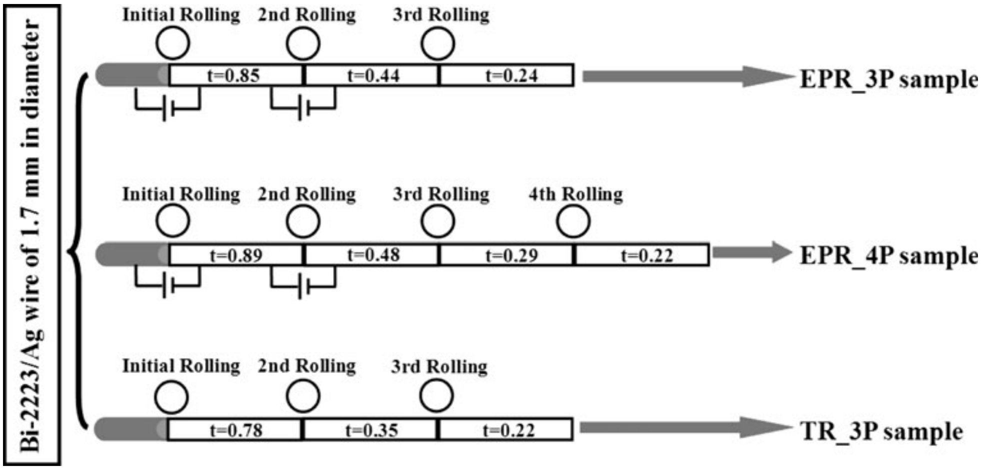


Fig. 2 Flow chart showing the rolling process for samples used in this study



of about 35–55% per pass. EPR_4P samples went through the same EPR process as those of EPR_3P, with two normal flat rolling processes carried out afterward, giving a final thickness of around 0.22 mm. In order to investigate the interface morphology, longitudinal cross-sections of these samples were observed using an optical microscope.

The three types of tape were cut into short specimens of 5 cm in length, and then sintered at 830 °C in 8.5% atm pO_2 for different time periods (3, 5, 10, and 20 h), followed by cooling at the rate of 100 °C/h down to room temperature.

The X-ray diffraction (XRD) patterns were measured of the peeled samples to analyze the phase transformation rate. The transformation rate of Bi-2223 (f_{2223}) from XRD patterns is defined by the following equation:

$$f_{2223} = \frac{I_{2223(00\underline{10})}}{I_{2223(00\underline{10})}+I_{2212(008)}} \qquad (1)$$

where $I_{2223(00\underline{10})}$ and $I_{2212(008)}$ are the integral intensities of the Bi-2223 (00$\underline{10}$) peak and Bi-2212 (008) peak, respectively. The microstructures of the 5-h-sintered EPR_3P and TR_3P samples were also observed using a LEO-1530 scanning electron microscope (SEM) in the backscattered electrons imaging mode.

After the Bi-2223/Ag wires were rolled to the flat tapes, and the tapes were heat treated at 830 °C, then followed by an intermediate rolling, second heat treatment, and post-annealing, the final products of 3.4 mm in width, 0.22 mm in thickness, and 10 m in length were obtained. Then measurements of I_c were carried out by a standard four-probe technique with a 1 µV/cm criterion at 77 K and self-field conditions.

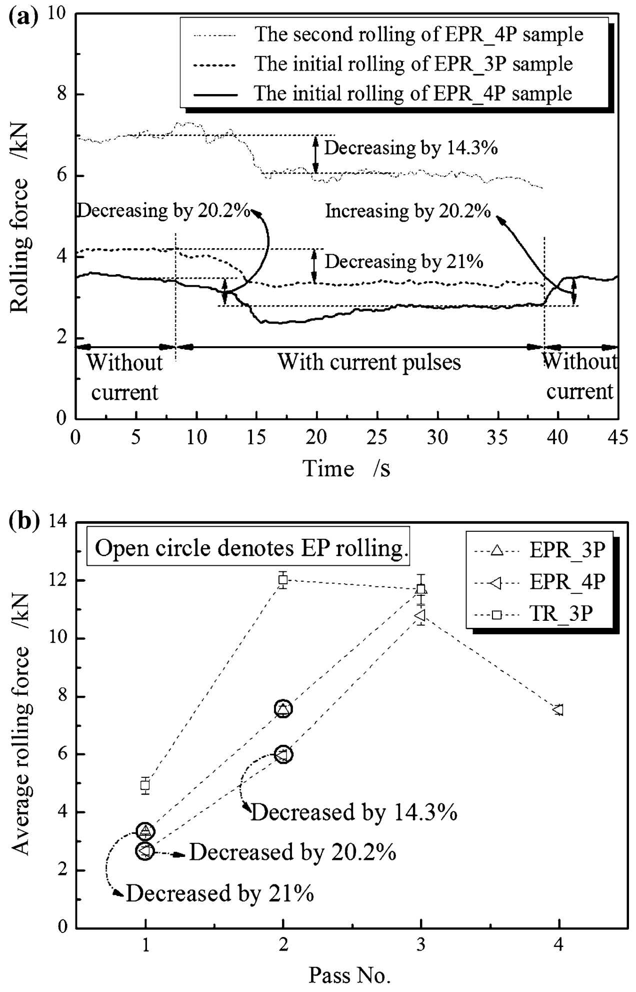


Fig. 3 The in situ rolling forces during the deformation processes: **a** Rolling force versus formation time with and without current pulses. **b** Averaged rolling force per pass for the rolling processes

Results and discussion

Rolling force

Plots of the actual rolling force versus time are shown in Fig. 3a. The decrease in rolling force started as soon as the current pulses were applied. After a very short period of time, the rolling force stopped declining and tended to be a constant value. It returned quickly to the initial value when the current pulses were shut off. At different rolling processes during EPR, the application of pulse current always has the potential to reduce the rolling force. Owing to the limitation of the device accuracy, compared with the same steps for EPR_3P and TR_3P tapes, the rolling force decline was not entirely attributed to EPR. However, the decline in the average rolling force during EPR far exceeded the error caused by the thickness reduction. As seen in Fig. 3b, it also shows that EPR led to a significant drop in the average rolling force compared to conventional rolling. The relative decrease in rolling force per pass reaches 14.3% and the maximum is 21%. The subsequent experiments reveal the superior mechanical characteristics of the superconducting wire obtained from EPR.

The rolling processes used to fabricate the Bi-2223/Ag wires have shown that the electroplastic effect can be obtained with a peak current density of about 10^3 A/mm^2, which suggests that electroplastic effect can be applied during the processing of Bi-2223/Ag wires. It is known that the metallic sheath enhances metal conduction and the superconducting powder has good insulating performance. Because of the electroplastic effect in metals, there exists a force acting on dislocations induced by drift electrons during EPR. The drift electron–dislocation interaction force would aid dislocations to overcome obstacles and lattice resistance, reducing the flow stress of metals. Of course, EPR also results in the temperature rising in deformation zone, but the rolling speed was controlled at 2 m/min, and the temperature should be in the range of

100–200 °C, with the result that it is not quite possible that the recovery of dislocations can take place in such a short time and the temperature should have some influence on the growth of the Bi-2223 phase. Therefore, the improvement in the mechanical properties of the metallic sheath causes a significant decrease in the rolling force of the composite tapes during EPR. In the conventional drawing process, it is necessary to anneal wires several times to reduce work hardening for further deformation. Based on the experimental results, it is feasible to process the Bi-2223/Ag wire by EPR, which not only increases the degree of deformation and reduces the number of required passes but also lessens the production cost.

Core uniformity

Several investigations [13, 14] have shown that the interface geometries between the silver sheath and the powder play an important role in obtaining a good texture, high powder density, and a high critical current in the tape. The sausaging effect has been a major problem in the processing of Bi-2223/Ag tapes. Han et al. have proposed a "powder flow" model to describe the behavior of Bi-2223/Ag wires during mechanical deformation. According to their theory, the degree of sausaging depends on the mass flow direction [15, 16].

In the TR process, the generation of sausaging in Bi-2223/Ag tapes is very sensitive to the rolling conditions. The use of larger diameter rollers tends to reduce the sausaging effect. For comparison, the roller diameter was fixed at 60 mm for all the three types of processing. As seen in Fig. 4, the longitudinal sections of the deformed tapes are quite different. After the final rolling process, interface instability was observed in the TR_3P samples. However, the interface between the powder and silver sheath was much smoother in the samples which were produced by EPR. During EPR not only the strength of metal but also the rolling force declines. Although the material softening is actually a negative effect for the rolling uniformity, the decrease in rolling force is more beneficial to the weakening of sausaging. Therefore, the reduced sausaging effect can be explained by the significant drop in rolling force which plays the dominant role. The J_c values for the tapes are shown in Table 1. From the data, it is confirmed that J_c for the tape by EPR is improved from 15522 to 19932 A/cm^2, and the standard deviation of critical current density is less than 760 A/cm^2 compared to the TR_3P tape. Because geometrical uniformities are associated with a high powder density and could lead to a higher current density, the weakening of sausages, meanwhile, leads to a better silver–super interface, which might improve the tape performance. Therefore, the geometries of the filaments obtained by EPR are desirable.

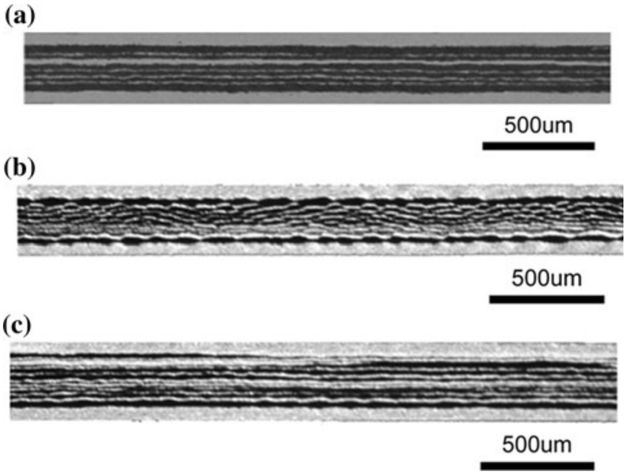


Fig. 4 Optical micrographs of longitudinal cross sections of the deformed tapes: **a** EPR_3P sample. **b** TR_3P sample. **c** EPR_4P sample

Table 1 The critical current density J_c for the samples with different process conditions

Sample	J_c (critical current density) (A/cm^2)	σ (standard deviation of J_c) (A/cm^2)
EPR_3P	19932	756
EPR_4P	15522	1770
TR_3P	14679	1983

Phase transformation of Bi-2212 to Bi-2223

The TR and EPR samples were sintered at 830 °C for different time periods. The transformation rate from Bi-2212 to Bi-2223 of these samples is shown in Fig. 5. All the three curves show an obvious dependence on sintering time, and the relative Bi-2223 phase content increases as

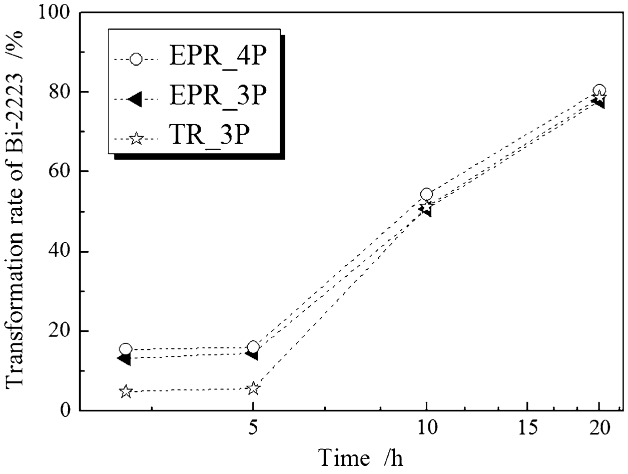


Fig. 5 The relative Bi-2223 phase content of samples at different sintering times

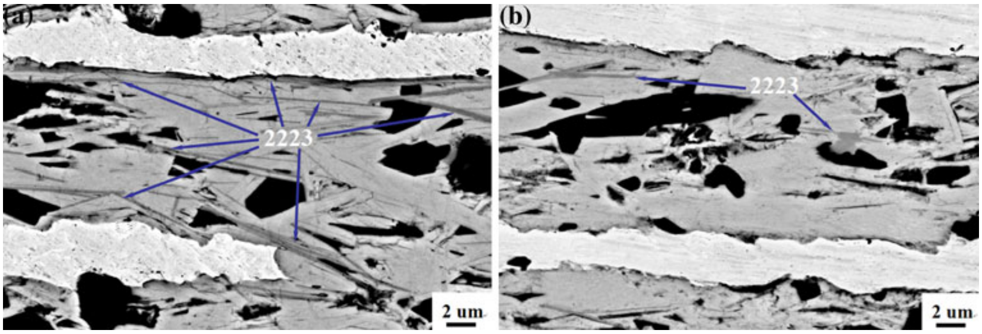


Fig. 6 Backscattered SEM photos of polished sections of the EPR_3P and TR_3P sample after sintering for 5 h. **a** EPR_3P sample. **b** TR_3P sample (*white regions* pure silver; *dark gray plates* Bi-2223; *light gray plates* Bi-2212; *dark regions* AEC or CuO)

the sintering time increases. All of the samples reach a saturated Bi-2223 phase content after sintering for more than 10 h. However, when sintering is less than 5 h, the phase transformation rate of the EPR samples is around two times higher than that of the TR_3P sample.

The phase transformation from Bi-2212 to Bi-2223 plays an important role in the first heat treatment. Different mechanical processes may lead to different deformation mechanisms, which might affect the formation of the Bi-2223 phase. There are no direct links between the EPR process and the growth of the Bi-2223 phase. However, it is possible that the EPR process could produce more homogeneous superconducting filaments, which could influence the formation kinetics of the Bi-2223 phase. It is apparent from Fig. 5 that the Bi-2223 phase grows faster in tapes fabricated using current pulses. These data presented in this study demonstrate that high-density current pulses contribute to the kinetics of the development of the preferential orientation.

Figure 6 shows backscattered SEM photos of polished sections of the samples after sintering for 5 h. The Bi-2223 and Bi-2212 phases are shown as the dark gray and light gray areas, respectively. The black regions correspond to some alkaline-earth cuprates (AEC) and CuO particles. As illustrated in Fig. 6, the EPR_3P tape exhibits more Bi-2223 grains than TR_3P tape, which can be evidenced from the calculations of the relative Bi-2223 phase content in Fig. 5. In the EPR_3P sample, the Bi-2223 phase mostly grows along the interfaces between the silver and ceramic powder, which is the most important current path in Bi-2223 tapes. This is a direct result of the high density and homogeneity of the superconducting filaments formed by EPR, which improves the mechanical deformation of the Bi-2223 tapes and enhances the kinetics for generating the 2223 phase after heat treatment.

At present, the application of high-density electrical pulses is found to be an effective method for improving the material properties and critical currents of superconducting tapes. Owing to small roller diameter, the critical current density achieved in the fully processed tape with EPR is about 20 kA/cm^2, still much lower than the industrial level of 30 kA/cm^2. The electroplastic processing technique is expected to increase the proportion of filaments in the cross-sectional area of the tapes by using larger rollers and reduce the manufacturing costs by optimizing the deformation process, implementing an increase in the critical current density of the superconductor tapes.

Conclusions

An EPR process was used to fabricate Bi-2223/Ag superconducting tapes by applying high-density current pulses during rolling. It was found that EPR can greatly reduce the rolling force and improve the deformation homogeneity, compared with the TR method. Also, the sausage effect can be reduced using the EPR process. The evolution of the Bi-2223 phase during the first heat treatment of the tapes was also studied. It was found that the current pulses during rolling contribute to the fast formation kinetics of the Bi-2223 phase in the EPR samples and a preliminary J_c improvement of about 28% in fully processed EPR_3P tape, which could be explained by their more homogeneous superconducting filaments than those of tapes prepared by the TR method, owing to the electroplastic effect.

Acknowledgements The authors wish to express gratitude to Professor G. Y. Tang for providing the research facilities used to undertake this study. This study was supported by the Major Program of the National Natural Science Foundation of China (Grant No. 50635050).

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