Advances in Engineering Research, volume 128

7th International Conference on Manufacturing Science and Engineering (ICMSE 2017)

Deformation analysis for the superconductor-silver interface in the Bi-2223/Ag tape rolling process

Yongjin Lu[1, a]

China Ship Development and Design Center, Wuhan, 430064, China

[a]soda1998@126.com

Keywords: Interface; Sausaging; Bi-2223/Ag; Rolling; Modelling

Abstract. Analytical model of interface deformation behavior during rolling process was established to investigate the principle of sausaging formation, and formula involving the geometric parameters and physical properties of silver layer was derived on the basis of energy approach. Moreover, the curvature difference of interface before and after deformation was defined as evaluation factor for the interface forming quality. Numerical model of Bi-2223/Ag high temperature superconducting wires during rolling was proposed, and the effect of process parameters such as inner tube material, roller diameter and friction coefficient on the deformation behaviors of the interface in Bi-2223/Ag wire was analyzed. The results suggest that inner sheath material with high strength contributes to a better silver-super interface. Simultaneously, larger roller and small friction coefficient weaken the interface instability and obtain the final tape with high critical current density. In addition, the numerical results verify the accuracy of the theoretical derivation.

Introduction

Most of the (Bi, Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_x$(Bi-2223/Ag) superconducting tapes are fabricated using the standard powder-in-tube (PIT) technique. In the PIT method, as one of the key techniques in the mechanical deformation, rolling processing for Bi-2223/Ag tape plays an important role in leading to strong c-axis texture, high density of the superconducting powder, and uniform distribution of microscopic and macroscopic deformation. Owing to the differences in material properties and irrationalities of process conditions, interface instability along the superconductor-silver interface has been a major problem in the rolling process, which reduces the critical current density (J_c) and mechanical properties of the final tape, as shown in Fig.1.

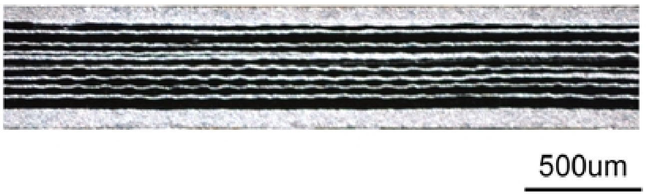


Fig.1 Sausage formation in longitudinal section of Bi-2223/Ag tape

At present, the critical current density and mechanical properties are the most important performance indicators of Bi-2223/Ag tapes. Numerous studies have been carried out on the relationship between superconductor-silver interface and tape performance[1~4]. In particular, the study performed by Larbalestier[2] was position-sensitive measurements of the highest J_c regions, which were close to the Ag sheath for individual superconducting filaments of Bi-2223/Ag tapes. Based on the Larbalestier's work, the texture at the interface region of the filaments affects J_c more significantly than that at the centers. Moreover, the well textured layer of Bi-2223 grains is supposed to be the result of smoother superconductor-silver interface.

In this study, the sausaging generation during the rolling process was analyzed, subsequent the evaluation indicators of silver-super interface were established and finite element analysis on interface deformation behaviors was performed.

Theoretical derivation of sausaging mechanism

For interface deformation behaviors, Han et al. have presented a “powder flow” model to explain the production of sausage effect and introduced the term ‘freedom parameter’ to illustrate the influence of various constraint factors on the mass-flow behaviour[5]. During the rolling process of Bi-2223/Ag wires, the generation of sausaging is similar to sheet wrinkling. Wrinkling is one of the main obstacles during sheet metal forming, which is caused by an unstable plastic deformation of sheet material[6]. Fig. 2 shows the analytical model of silver layer with unit length along the x axis. The stress p_1, p_2 are induced by the compressive force of powder on the both sides of silver layer, respectively. The mean stress caused by the combination of the traction of rolling force and uneven flow of powder can be regarded as the compressive stress $\bar{\tau}$.

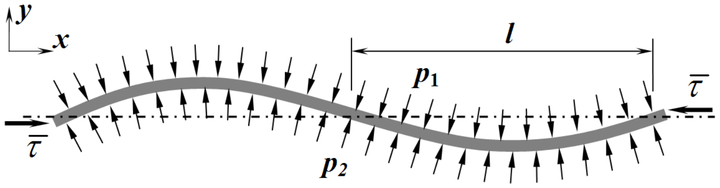


Fig.2 Mechanical analysis on the silver layer of the Bi-2223/Ag tape

Based on the geometry condition, material property and stress condition of the silver layer, the energy method is used to analyze the sausaging effect. Assume that the waveform of silver layer could be expressed as sine curve in the following form:

$$y=A\sin(N\pi x/L). \tag{1}$$

where A is the amplitude, L is the tape length, N is the number of single-waves in the tape with length L.

For the formation of sausage phenomenon, the energy involved in the rolling deformation can be attributed to three parts of contents: First, bending energy U_b is consumed on the bending of the silver layer; Second, in the deformation zone, the uneven flow of powder makes the silver layer under compressive stress $\bar{\tau}$. As the silver layer length is shortened, the stress $\bar{\tau}$ releases energy U_s; Third, silver layer withstands the pressure from powder along thickness direction, and the energy on the consumption of pressure each half-wave is U_p.

Based on the energy conservation, the following relation holds:

$$U_s = U_b+U_p. \tag{2}$$

According to the energy of elastic bending formula by mechanics of materials, elastic modulus E is replaced by reduced modulus E_r, bending energy U_b can be given by

$$U_b = \int_0^l \frac{E_r I}{2}\left(\frac{d^2 y}{dx^2}\right)^2 dx. \tag{3}$$

where I denotes the moment of inertia for the silver layer with thickness t and unit width.

Combining formula (1) and (3) yields

$$U_b = \int_0^l \frac{E_r}{2}\left(\frac{AN^2 p^2}{L^2}\sin(Np\,x/L)\right)^2 \frac{t^3}{12}dx = \frac{E_r A^2 N^3 p^4 t^3}{48L^3}\ . \tag{4}$$

During the sausaging formation, the single wave length is shortened, and the variation can be expressed as

$$\Delta l = \int_0^l \mathrm{d}C - \int_0^l \mathrm{d}x \ . \tag{5}$$

where dC and dx represent single-wave arc length and its projection in the x axis, respectively. And dC can be given by

$$\mathrm{d}C = \sqrt{\mathrm{d}x^2 + \mathrm{d}y^2} = (1 + \frac{1}{2}(\frac{\mathrm{d}y}{\mathrm{d}x})^2 + \cdots)\mathrm{d}x \, . \tag{6}$$

Ignore the higher than second-order items in the formula (6), then

$$\Delta l = \int_0^l (1 + \frac{1}{2}(\frac{\mathrm{d}y}{\mathrm{d}x})^2)\mathrm{d}x - \int_0^l \mathrm{d}x = \frac{1}{2}\int_0^l (\frac{\mathrm{d}y}{\mathrm{d}x})^2 \mathrm{d}x \ . \tag{7}$$

Combining formula (7), U_s can be written as

$$U_\mathrm{s} = \bar{\tau} t \times 1 \times \Delta l = \bar{\tau} t \times \frac{1}{2}\int_0^l (\frac{\mathrm{d}y}{\mathrm{d}x})^2 \mathrm{d}x = \frac{\bar{\tau} t A^2 N p^2}{4L} \, . \tag{8}$$

In the deformation process, the powder compression occurs on the both sides of the silver layer, which makes the silver under pressure. Assume the modulus of the supporting as $\bar{p}$, which is similar to the stiffness in Hooke's Law and relation to p_1 and p_2. The force acted on the silver of length dx is $\bar{p}y\mathrm{d}x$, then U_b can be written as

$$U_\mathrm{p} = \int_0^l \bar{p} y^2 \mathrm{d}x / 2 = \frac{\bar{p}A^2}{4}\int_0^l (1 - \cos(2Np\, x / L))\mathrm{d}x = \frac{\bar{p}A^2 L}{4N} \ . \tag{9}$$

Combining equation (2), (4), (8) and (9) yields

$$\frac{\bar{\tau} t A^2 N p^2}{4L} = \frac{E_\mathrm{r} A^2 N^3 p^4 t^3}{48L^3} + \frac{\bar{p} A^2 L}{4N} \, . \tag{10}$$

Through the mathematical differentiation of the formula (10), let $\partial\bar{\tau} / \partial N$ be zero, then the wave number N in the critical state can be given by

$$N = \frac{L}{p\, t^{0.75}} \sqrt[4]{12\bar{p} / E_\mathrm{r}} \ . \tag{11}$$

Substituting formula (11) into formula (10), the minimum of compressive stress $\bar{\tau}$ obtains

$$\bar{\tau}_{\min} = E_\mathrm{r} \frac{L^2}{p^2 t^{1.5}} \sqrt{12\bar{p} / E_\mathrm{r}}\, p^2 t^2 / (12L^2) + \bar{p}L^2 / (\frac{L^2}{p^2 t^{1.5}} \sqrt{12\bar{p} / E_\mathrm{r}}\, p^2 t) = \sqrt{3\bar{p}E_\mathrm{r} t} / 3 \ . \tag{12}$$

According to formula (12), the generation of sausaging in Bi-2223/Ag tapes is very sensitive to silver layer thickness, material properties and rolling conditions. In order to avoid the occurrence of sausage effect, the following equation is obtained

$$\bar{\tau} \le \sqrt{3\bar{p}E_\mathrm{r} t} / 3 \, . \tag{13}$$

where, $\bar{t}$ and $\bar{p}$ comprehensively reflect the process parameters of Bi-2223/Ag tapes. E_r and t are the yield strength and silver thickness, respectively.

The evaluation indicators of silver-super interface

To analyze the silver-superconducting interface, the curvature difference ΔK is defined to evaluate the interface fluctuations, as shown in figure 3.

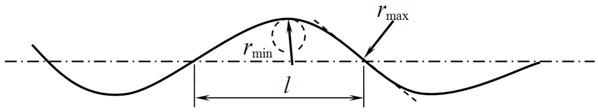


Fig.3 The definition of evaluation indicators of silver-super interface in the multifilamentary wires

During the calculation of evaluation indicators, it is necessary to extract the curve geometry of silver-super interface after deformation and calculate the evaluation indicators. The calculation of curvature radius is shown as Fig. 4, for all points, the curvature radius of per three consecutive points is calculated successively, and the minimum value $r_{\min}$ is obtained by comparison. For three consecutive points A, B, C, assume the coordinates as (x_1, y_2), (x_2, y_2) and (x_3, y_3), respectively.

The distance a between two points A and C can be written as

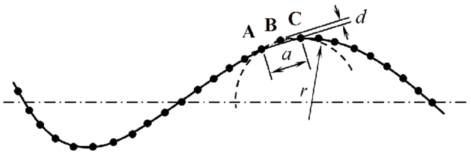


Fig.4 The calculation of radius of curvature on the silver-super interface

$$a=\sqrt{(x_3-x_1)^2+(y_3-y_1)^2}\ . \tag{14}$$

The distance d from point B to the straight line with two points A and C can be written as

$$d=\left|(y_3-y_1)/(x_3-x_1)x_2-y_2-(y_3-y_1)/(x_3-x_1)x_1+y_1\right|/\sqrt{(y_3-y_1)^2/(x_3-x_1)^2+1}\,. \tag{15}$$

Based on Pythagorean theorem, combining formula (14) and (15), the curvature yields

$$K=1/r=2d/(d^2+a^2/4)\ . \tag{16}$$

$$\Delta K=\mathrm{Max}\{\left|1/r_1-1/r_1'\right|,\left|1/r_2-1/r_2'\right|\ldots\left|1/r_i-1/r_i'\right|\}\,. \tag{17}$$

where r_i, r_i' are the radius of curvature at the same point i before and after deformation, respectively.

The geometric meaning on the minimum radius of curvature implies the greatest convex curve or the maximum concavity of silver-super interface.

Simulation results and discussion

Numerical simulation is used to investigate the interface deformation behaviors during rolling process and the influence of process parameters on the interface stability.

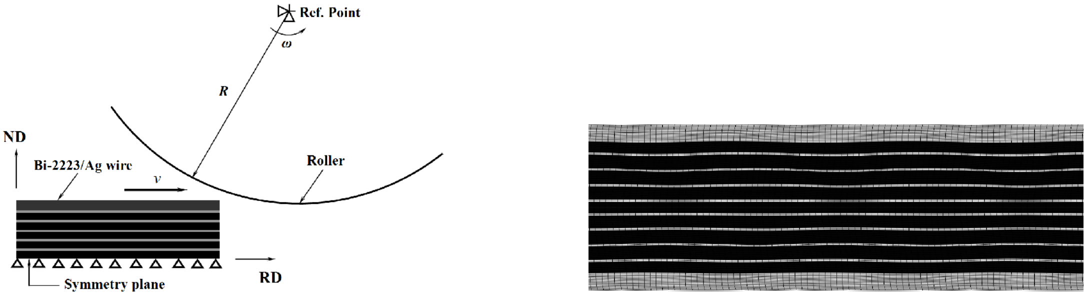
FEA model and verification

Owing to large deformation and nonlinear problems, the commercial finite element code ABAQUS/Explicit is employed to simulate the rolling process for Bi-2223/Ag tape. In this model, the modified Drucker-Prager/Cap elastic-plasticity theory is utilized as a constitutive model of superconducting powder, the pure Ag and Ag alloy are determined as continuum model, the input parameters are extracted from the refs. [7~9]. Because of symmetry, the numerical model is employed a plane strain representation, as shown in Fig. 5 a.

In the numerical simulation, the roller diameter was 60 mm, the friction coefficient between the roller and composite materials was 0.15, and the theoretical density of powder was 3.935 g/cm^3. After the rolling process, Bi-2223/Ag wire with a diameter of 1.7 mm was deformed to a tape of 0.89 mm in thickness, longitudinal cross section of the deformed tape is observed as shown in Fig.5 b, which is similar to the experimental figure. In order to quantitatively analyze the deformation on the superconducting core, the graphics measurement software based on VB program was used to measure displacement in the figure. Combined with the digital image processing technology, the normal strain of layers of superconducting core is obtained in Fig.6. Compared with the experimental figure, most regions of the simulation results are basically consistent with the experimental results, in addition to a small number of regional errors up to 10%, which verifies the feasibility of numerical simulation.

Influence of the material properties on the interface deformation behaviors

According to characteristic of strip preparation, sheath material is one of key parameters for Bi-2223/Ag tapes, should meet the following requirements: a) Workability; b) High hardness and strength; c) Oxygen permeability property; d) Good chemical stability; e) High resistivity. As the silver and silver alloys can meet these requirements, silver is mainly used as the inner tube material and silver alloy is used as outer tube structure during the preparation of Bi-2223/Ag tapes.



(a) FEA model (b) Numerical figure after rolling

Fig.5 FEA model and numerical figure after flat rolling for superconducting wire

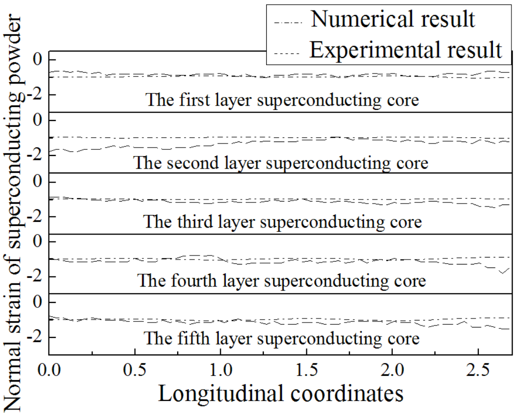
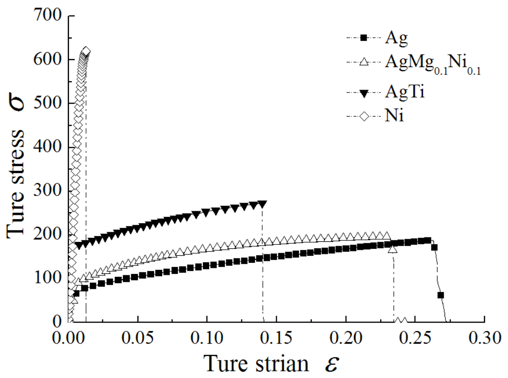


Fig.6 Normal strain of superconducting powder after flat rolling in FEM and Exp.

Grivel[10] replaced the outer sheath material by nickel and improved the mechanical stability and current performance of composite. Liang[11] investigated that the superconducting tapes using silver alloy as the outer tube and inner tube had the better mechanical strength compared to the commercial tapes. In order to investigate the influence of inner tube material on the silver-super interface, pure silver material is replaced by AgTi, $AgMg_{0.1}Ni_{0.1}$, Ni respectively. In this study, uniaxial tensions of different material at a constant deformation rate were performed at room temperature, a series of stress-strain curves are shown in Fig. 7. Ni has the highest strength, while the strength of pure silver is the worst. Figure 8 illustrates the simulation result of the relationship between the curvature difference and different materials. The size and standard deviation of ΔK increase with the decrease of yield strength for sheath materials, it indicates that the superconducting tapes using Ni as the inner tube have the smoothest interface and the best mechanical strength. Combined with the formula (13), the interface deformation behavior responds to the characteristics of the sheath material, the interface stability enhances with the increase of the material strength, which proved the reliability of numerical simulation.



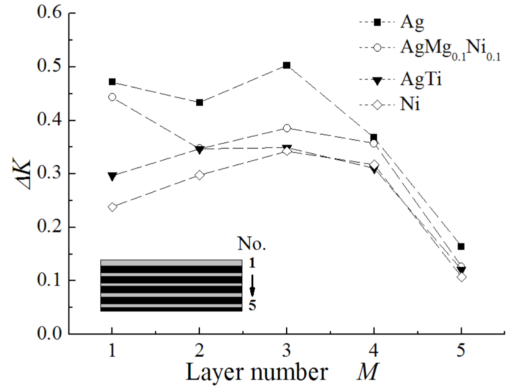


Fig.7 The stress-strain curves of various materials Fig.8 ΔK distribution in layers with different materials

Influence of the rolling diameter on the interface deformation behaviors

It is well-known that the differences of roll diameter make different material flow and the distribution of powder density. Therefore it is essential to investigate the rolling diameter on the interface deformation behaviors. The numerical models are established under the same rolling parameters with different rolling diameters as following: 60, 90, 120 and 150 mm, respectively. Fig.9 shows that larger rolling diameter weakens the interface instability. Meanwhile, the weakening of sausages leads to a better silver-super interface, which might improve the tape performance. A small roller diameter causes more obvious sausage effect along interface between silver layer and the superconducting core. Nevertheless, when the diameter is larger than 120 mm, the interface flatness does not change significantly. It can be explained that the increase of roll diameter makes the contact area between roll and deformed tape increase and leads to a drop in the compressive stress $\bar{t}$ in the formula (13).

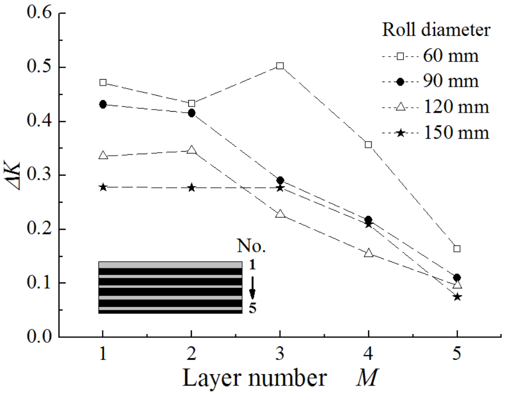


Fig.9 ΔK distribution in layers with different rolling diameters

Influence of the friction coefficient on the interface deformation behaviors

During rolling process, friction force from deformation zone impedes the flow of materials. The influence of the friction coefficient during the forming process is discussed with the same rolling parameters as following: 0.15, 0.25, 0.35 and 0.45. The curvature difference in the multifilament tape results from the increase of the friction coefficient, as seen in figure 10. According to the formula (13), the augmentation of the friction coefficient increases the compressive stress $\bar{t}$, the formula may not be hold and the sample could develop a wavy interface between the Ag matrix and the ceramic core.

Therefore, lubrication can improve the interface forming quality and it is essential that effective measure be taken to improve the lubrication condition.

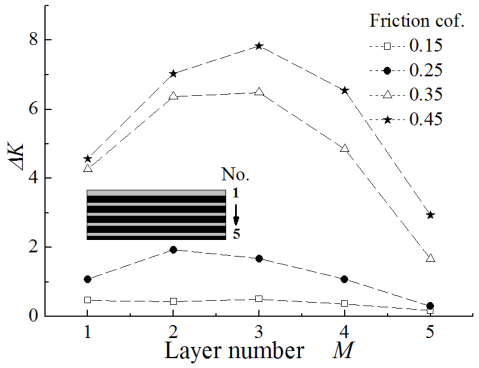


Fig.10 ΔK distribution in layers with different friction coefficients

Conclusions

Based on the energy approach, a theoretical model for silver layer was employed to explain the formation of sausaging, it was revealed that larger yield strength and silver layer thickness favorably minimized the sausage effect. Moreover, a criterion was established for the interface geometry evaluation. In order to investigate the interface deformation behaviors, the numerical modeling of Bi-2223/Ag under rolling process was constructed in this paper. It was found that the superconducting tapes using high-strength material as the inner tube have the smoothest interface and the best mechanical strength. Also, larger rolling diameter and small friction coefficient lead to a better silver-super interface and might improve the tape performance. Besides, the numerical results are consistent with the accuracy of the theoretical derivation.

Acknowledgements

The authors wish to express gratitude to Dept. of Mechanical Engineering Tsinghua University for providing the research facilities used to undertake this work.

References

[1] G. Grasso, B. Hensel, A. Jeremie, et al. Lateral distribution of the transport critical current density in Bi(2223) Ag-sheathed tapes. Applied Superconductivity, 148, 463-466, 1995

[2] D. C. Larbalestier, X. Y. Cai, Y. Feng, et al. Position-sensitive measurements of the local critical current density in Ag sheathed high-temperature superconductor (Bi, Pb)2Sr2Ca2Cu3Oy tapes: The importance of local micro- and macro-structure. Physica C, 221, 299-303, 1994

[3] S. S. Oh, J. K. Choi, H. S. Ha, et al. Texture development of a multi-filamentary Bi2Sr2Ca2Cu3Ox HTS tape during thermo-mechanical treatment. IEEE Trans. Appl. Supercond., 13(2), 2960-2963, 2003

[4] M. Lelovic, P. Krishnaraj and N. G. Eror, Minimum critical current density of 105 A/cm2 at 77 K in the thin layer of Bi1.8Pb0.4Sr2.0Ca2.2Cu3.0Oy superconductor near the Ag in Ag-sheathed tapes. Physica C, 242, 246-250, 1995

[5] Z. Han, P. Skov-Hansen and T. Treltoft, The mechanical deformation of superconducting BiSrCaCuO/Ag composites. Supercond. Sci. Technol., 10, 371-387, 1997

[6] A. M. Szacinski, P. F. Thomson, Investigation of the existence of a wrinkling-limit curve in plastically-deforming metal sheet. J. Mater. Proc. Tech., 25, 125-137, 1991

[7] M. Eriksen, J. I. Bech, B. Seifi, et al. 3-dimensional numerical modeling of rolling of superconducting Ag/BSCCO tape. IEEE Trans. Appl. Supercond., 11(1), 3756-3759, 2001

[8] Y. H. Zhao, P. Zeng, L. P. Lei, et al. Experimental investigation on constitutive behaviour of superconducting powder BSCCO. J. Mater. Sci., 42, 4692-4700, 2007

[9] Y. J. Lu, P. Zeng, L. P. Lei, et al. Optimization of cross-sectional shapes of the Bi-2223/Ag wires before flat rolling, Chinese Journal of Mechanical Engineering, 22(6), 890-895, 2009

[10] J. C. Grivel. Composite metallic sheathes: the key to low-cost, high strength (Bi, Pb) 2Sr2Ca2Cu3O10-based tapes? Supercond. Sci. Technol., 20, 1059-1064, 2007

[11] T. Liang, T. M. Qu, P. Li, et al. Mechanical Properties of (Bi, Pb)-2223 Multifilament Tapes with Ag-Alloy Sheath. Chinese Physics Letters, 23, 964-966, 2006