Performance limits in REBCO tape for variation in winding parameters of CORC® cable and wire

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ABSTRACT

The design and testing of high current superconducting cables made of $\text{ReBa}_2\text{Cu}_3\text{O}_{7-x}$ (REBCO) are still under development. It seems to have huge potential to overcome some of the difficulties associated Low Temperature Superconductors. One of the attractive features of CORC® cable compared to other cable types is that a former with a small diameter can be used. This allows a flexible and round wire shape of the cable showing symmetry in the radial direction. This paper aims at analyzing limitations of a simple superconducting CORC® cable design by varying parameters such as substrate thickness, copper stabilizer layer thickness, winding angle, and central former diameter. The CORC® cable modeling is started from the design to the production stage of the tape, then the winding of the tape over the central former is performed at room temperature. The winding is critical as in the process, compressive strain is induced in the tape. This paper also investigates the influence of different parameters on the performance and possible performance degradation of superconducting CORC® wire and cable. The result showed that Hastelloy thickness decreases from 0.05 to 0.02 mm, at 1 mm core diameter, the variation of maximum strain is 47 % and 52%, at 0.01 and 0.02 copper thickness respectively. The compressive strain is increased by 43 % when the core diameter decreases from 3 to 1 mm, at 0.02 mm Hastelloy thickness. Similarly, at 0.01 mm copper thickness, and 0.05 mm Hastelloy thickness, 50% increase of compressive strain is noted when the core diameter decreases from 3 to 1 mm.

1. Introduction

Second generation high-temperature superconductors (HTS), also known as coated conductors or rare-earth-barium-copper-oxide (Rare-Earth $\text{Ba}_2\text{Cu}_3\text{O}_{7-x}$ or REBCO) tapes, are promising candidates for future superconducting cables and magnets [1]. In comparison with LTS, these materials possess superior mechanical properties, large current densities at very high magnetic fields, and elevated operating temperature [2]. This enables simplifications in the cryostat design and in the cooling of the magnets. Being a new technology, extensive studies are needed for HTS conductors and magnets so as to understand their performance under different electromagnetic, mechanical, and thermal loading conditions. The effects of these loading conditions have to be assessed not only in their application stage but also considering the basic production stages of tapes and their wire and cable winding phase. When the strains developed under these different loading conditions pass beyond a certain limiting threshold, the strain irreversibility limit, the material

will start losing its superconducting property and become irreversibly degraded.

Determination of the optimum configuration for tape and cable, their operating conditions and the influence of various other parameters the performance of the cable are necessary. K Ilin et al. performed extensive experimental testing and detailed FE modelling on REBCO superconducting tape for various mechanical loading cases as a basis for predictive modeling of CORC® cable [3]. The CORC® wires and cables were first introduced by D.C. van der Laan [4]. For REBCO tape, different types of cabling methods like Conductor On Round Core [4], Twisted Stacked- Tape Cable [5,6], Roebel Assembled Coated Conductor Cables were proposed [7–9]. At the University of Twente, a detailed FE model was developed for a six-layer superconducting CORC cable that describes the mechanical effects from the basic tape manufacture to cable bending for coil winding [10].

Parametric model studies on superconducting CORC cable were also presented by K. Wang et al. [11]. A homogenization was applied by

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weighting Young's moduli of the superconducting, substrate, and copper layers according to the volume fraction of each material, further assuming the materials to be fully elastic. Consequentially, Wang et al. considered the multi-layered tape made of different materials such as copper, hastelloy, REBCO, etc. (as shown in Fig. 1) as a homogeneous material for their analysis. An important factor that influences the tape performance during its structural loading is the residual stress already within the material; however, the effect of residual stress was not taken into consideration in their work. In the case of REBCO tapes, the residual stress is expected to be prominent due to the thermal loading involved during its production process. It may be recalled that these tapes are subjected to a wide temperature variation from 1020 K to room temperature/77 K while it is being produced. Therefore, it would be more practical to consider the residual stress already developed in the tape material for modelling and analysis of its winding process. Additionally, Wang et al. computed average strain developed within the tape material throughout their studies. Based on the experimental studies, if the compressive strain axially developed in the REBCO layer exceeds beyond 0.4 %, the tape may lose its superconductivity and is considered degraded [3,12], and [13]. Therefore it would be more reasonable to consider the maximum strain developed than the average value of strain.

Critical current strongly depends on the strain in the REBCO tape and once the strain is reached beyond a value, critical current starts degrading. The winding angle is also an important parameter which influences the strain sensitivity. It can be expressed with the power law of strain dependence of critical current, for REBCO coated conductors produced by IBAD-MOCVD method [14–16]. D C van der Laan et al. reported that strain sensitivity is maximum at zero or 90 degrees winding angles [12]. Critical current initially increases with applied strain, due to the residual strain developed during the production process. So the residual strain is also an important parameter to evaluate maximum critical current. The recent development in the CORC cable shows that significant rise in the current density and also their flexibility can be attained with the help of smaller substrate. REBCO tape from the Super power cable retains full critical current when the substrate thickness become 50 μm , 38 μm , 30 μm , 25 μm , 20 μm for 4 mm, 3 mm, 2.3 mm, 2 mm, 1.6 mm core diameter respectively [14].

All models reveal that the strains at the edges of the HTS tape are larger than in the center region. Even though several studies are carried out on REBCO cables [14], till now there are not many HTS magnets developed. It may be noted that the experimental validation of conductor designs and particularly their design optimization are expensive. Therefore, in this study, an attempt has been made to model the winding of REBCO CORC® cable using COMSOL Multiphysics® to investigate possible conductor optimization for different applications and different tape geometries. Some of the parameters that are significant but not considered by the previous researchers are taken into account in this study. The tape will be considered to be made of different material layers and the production process of the tape is also modelled to determine the residual stress induced within the material.

2. Modeling approach

The Solid Mechanics module in the COMSOL Multiphysics® tool is used to create a single layer CORC winding. The mathematical prototype of the tape is created to determine the range of each parameter within which the cable is not degraded. The parameter monitored is the irreversibility limit of the strain developed. This type of study using a mathematical model will help to avoid series of experiments demanding more time and cost. Besides, eventually, parametric analyses can be used to find the optimal cable design for specific applications.

The configuration of the Superpower REBCO tape used for the analysis is given in Fig. 1. It consists of different layers on a substrate made of Hastelloy. The concern while using a superconducting tape is the strain developed in the REBCO layer due to the effect of other layers under different loading conditions. However, it may be noted that out of the different layers, the thickness of the Hastelloy substrate and copper stabilizer is dominant. Therefore their influence on the strain developed in the REBCO layer will be significant compared to the other much thinner layers. For the modeling, REBCO, Copper, and Hastelloy layers are considered and the other layers are neglected. This type of simulation approach has already been experimentally validated and followed by other researchers [3,5,11].

During the production state, residual stress and strain are developed in the tape. The REBCO tape production process consists of two main steps. In the first step, the REBCO film is deposited on the substrate by using the Metal-Organic Chemical Vapor Deposition (MOCVD) method at 1020 K. Then it is cooled to 333 K at which the copper electroplating is done to create the copper stabilizing layers. After that, it is cooled down to room temperature. The Birth and Death method [3,18] is used for the tape production process. MOCVD process can be simulated by providing initial (1020 K) and final temperature (333.15 K) to Hastelloy and REBCO. The challenge is in modelling electroplating of copper because the layers need to be added on a deformed configuration resulting from initial cool down. During initial cool down (1020 K -333.15 K) passive copper layer is also allowed to deform freely without contributing any stress. This is done by providing a very low value of Young's modulus of the copper. In modelling second cooldown step Hastelloy, copper and REBCO are given temperature load of 333.15 K to operating temperature [19]. The used material properties of REBCO, Hastelloy, and Copper used are listed in Table 1 [3].

At room temperature, the REBCO tape is wound around a central former [4]. The diameter of the central former is varied to analyze its influence on possible degradation of the tape during the winding process. Materials such as Copper, Hastelloy, and REBCO are considered isotropic in the simulation. Since REBCO is showing elastic behavior in the whole range of temperatures, it is considered elastic for the modeling. But for Copper and Hastelloy the plastic behavior is taken into consideration.

Fig. 1. Configuration of the REBCO Superconducting tape produced by SuperPower®, the 2G HTS tape SCS4050 [17].

Table 1
Material properties [3].

Material	Young's modulus (GPa)	Yield stress (MPa)	Poisson's ratio	Thermal expansion coefficient (K^{-1})
Hastelloy (RT)	223	891	0.307	1.34×10^{-5}
Hastelloy (77 K)	228	1141	0.307	1.34×10^{-5}
Copper (RT)	80	120	0.34	1.77×10^{-5}
Copper (77 K)	98	146	0.34	1.77×10^{-5}
REBCO	157	–	0.3	1.1×10^{-5}

3. Mesh and boundary conditions

The tape has been meshed finer than the former as it is one of the requirements when dealing with problems involving contact. The mesh independent study was carried out by varying the number of elements as width and lengthwise. Taking 8 elements widthwise and 200 elements lengthwise, lead to good results for all winding angles. These results are similar to the model with finer meshes. Therefore, for all the subsequent models, the tape has been meshed with 200 elements along the length and 8 elements along the width. The thickness of the tape is taken such that each material chosen has one element in thickness. Therefore, the tape is four elements thick with one layer of Hastelloy and REBCO along with two layers of Copper. The mesh in the contact layer of the tape is refined by inserting diagonal elements to ensure proper contact during winding. It may be noted that, since geometry contains a thin layer of materials, the tape will have high aspect ratio. The attempt to reduce the aspect ratio will give rise to a large number of elements and computationally it will be more involved.

The contact pair corresponding to the tape is considered as the destination pair and the periphery of the cylinder is taken as the source. There are two methods by which the contact can be realized in COMSOL Multiphysics; the Augmented Lagrangian and Penalty methods. The augmented Lagrangian method is considered more accurate; but, it has a higher computational cost and requires more fine-tuning to converge [20]. The Penalty method is relatively less accurate but more robust and needs less solver tuning. So, the Penalty method is used here to get faster convergence. The boundary conditions provided are as follows: the rigid connector boundary condition is applied to one surface of the central former to apply the rotation and translational movement of the central former. Similarly, rotational and translational movement is applied to the REBCO tape surfaces as shown in Fig. 2. A boundary load of 50–100 MPa is applied to the opposite end of the REBCO tape and the prescribed displacement perpendicular to the tape surface is restricted to zero. It may be noted that in actual practice winding stress generally maintained between 50 to 100 MPa. The convergence is verified through mesh independent study and by continuously monitoring the convergence plot. The damping factor is also adjusted to obtain a better convergence. The initial tolerance limit was set to 0.001 which was later increased to 10^{-6} .

Fig. 2 also shows the relative movements of the central former and the tape during the process of winding. The enlarged sectional view of

Fig. 2. Mesh and boundary conditions: REBCO tape and central former.

the tape is given in Fig. 3. The REBCO layer is deposited on the Hastelloy substrate and is protected with copper layers at the sides. It may be noted that while winding, the side with REBCO tape will be facing the central former.

4. Results and discussion

4.1. Experimental validation

The development of the numerical model of the REBCO CORC cable has been completed and several parametric studies have been carried out. The various parameters considered for the studies are central former diameter, winding angle, substrate thickness, copper layer thickness, and tape width. For all these cases, the strain developed in the REBCO layer is computed to assess the threshold criterion for irreversible critical current degradation. To ensure that the superconducting cable is not degraded, the intrinsic axial tensile and compressive strain in the REBCO layer should not exceed 0.45 and -0.40% respectively [3, 12,13].

The validation of the mathematical model has been carried out using the available experimental work in the literature [3]. The performance of SuperPower® REBCO tape has been experimentally evaluated in a critical current-strain-testing rig by C. Zhou et al. [21]. The results obtained in their experimental work have been compared with the simulation results of this study.

Fig. 4 shows the intrinsic strain versus applied strain in the REBCO tape during tensile loading at liquid nitrogen temperature. Fig. 5 shows the stress versus applied strain in the REBCO tape during tensile loading at room temperature. Both experimental and simulation results show fair agreement and the maximum variation between the simulation and experimental results is 1.8%. It may be noted that when the tensile intrinsic strain reaches 0.45%, leading to degradation of REBCO tape, the stress developed in the REBCO tape is 861 MPa and the applied strain is 0.7 %. It has also been found that within the acceptable range of tensile strain. This simulation model is used for carrying out the parametric studies.

As mentioned earlier, degradation of the superconducting material can happen not only in their application stage but also during winding the tapes around the former. The strain developed in the production state and also in the winding has been evaluated using the numerical model.

4.2. Residual strain in REBCO layer

In this study, it was found that during the production stage, when the tape is cooled from 1020 to 293 K the intrinsic axial strain developed in the REBCO layer is -0.17%. When the tape is further cooled to liquid nitrogen temperature, the intrinsic axial strain becomes -0.24%, as shown in Fig. 6. These results are in good agreement with earlier published work [3]. This residual strain developed due to temperature variation is taken into consideration for the rest of this work.

4.3. Strain during cabling

The winding stage is an important phase in the preparation of CORC cable that contributes to strain alterations in the superconducting material. During the winding, the compressive strain is induced in the REBCO layer because the tape side with the REBCO layer below the neutral axis is facing the central former. The initial modeling of the winding is carried out with an arbitrary diameter of 3 mm for the central former, a tape width of 4 mm, and a winding angle of 45°.

The distribution of the intrinsic strain in the REBCO layer after the winding is depicted in Fig. 7. The deviating strain pattern developed at the end of the tape is due to its fixation, needed for the mechanical forces during winding. The strain distribution at the central portion across the width of the tape is shown in Fig. 8. It has been found that, in the process

Fig. 3. Enlarged sectional view of the REBCO Tape.

Fig. 4. Intrinsic strain vs applied strain in the REBCO layer at room temperature.

Fig. 5. Stress vs percentage of applied strain in the REBCO tape at room temperature.

of the winding, the REBCO layer has a maximum compressive intrinsic axial strain of -0.45%. The strain varies from -0.06% to -0.45% across the tape width mainly caused by bending and twisting leading to a strain distribution.

The compressive strain is very prominent at the central portion of the tape as compared to the side ends. It is also visible that the results obtained are practically axial-symmetric across the width of the tape. In the central portion, these values are almost constant. This is because REBCO tape is largely subjected to bending and the REBCO layer is placed eccentrically at the inner side of the tape, closest to the former.

4.3.1. Variation of central former diameter

When the CORC cable is made, one important parameter that results in the generation of strain is the bending radius. The diameter of the

central former is varied in five steps; 1 to 7 mm, as shown in Fig. 9.

The effect of variation in intrinsic axial strain in the REBCO layer across the width, when wound on central formers of different diameters is shown in Fig. 10. The width of the tape is 4 mm. The graph shows that the distribution of intrinsic axial strain across the width of the tape remains axis-symmetric for all diameters.

When the central former diameter increases, the compressive strain developed in the REBCO layer decreases. This is because the bending radius decreases, resulting in lesser compressive bending strain. When the central former diameter increases from 1 to 7 mm, the compressive strain decreases. The core diameter increases from 1 mm to 7 mm, the intrinsic compressive strain decreases by 75 percent in the REBCO layer.

The results obtained are in close agreement with a similar study reported in the literature [11]. The trend in the variation of axial strain along the width of the tape for different core diameters is the same for both the studies. However, as compared to the previous work, the values obtained for the axial strain for this work is slightly higher in most cases. This may be because maximum strain developed is plotted in this study than the average strain developed. The differences in the values may be due to the homogeneous assumption of the tape by the previous work as compared to the modelling of tape as layers of different materials in this work. Also in the present work, the effect of residual stress is considered and it may increase the strain induced in the tape during the winding.

It is understood that decreasing the central former diameter results in the development of higher compressive strain. However, the use of a smaller central former can be of great advantage in practice since it approaches the desirable small round wire diameter range with high current density [12]. An attempt has been made to find the limiting diameter for the central former beyond which the strain developed is not in the acceptable range. The diameter of the central former is reduced from 7 to 1 mm in eight steps as shown in Fig. 11. Important to mention is that the Hastelloy substrate thickness is still taken as 50 μm and the copper stabilizer thickness 20 μm on both sides.

The compressive axial strain increases with the decreasing diameter of the central former. The limiting strain is -0.4% [12] and for the central formers with diameter 3.43 mm, the maximum compressive axial strain is beyond this value and therefore can't be used. Besides, it can be mentioned that the critical current reduces under high compression [13].

4.3.2. Variation in winding angle

The winding angle has a significant influence on the generation of strain in the REBCO tape. The generation of strain for five different winding angles has been computed, starting from zero to 60° in steps of 15°. The thickness of the Hastelloy substrate is 50 μm and the copper stabilizer thickness is 20 μm on both sides.

Fig. 12 depicts that as the helix angle increases, the bending curvature of the superconducting tape decreases gradually. This results in a decrease in the axial compressive strain in the REBCO layer. The generation of axial strain across the width of the tape is at maximum in the 0° case where the effect of twisting of the layer is absent. The detailed

Fig. 6. Residual strain in the REBCO layer during the production stage of REBCO tape.

Fig. 7. Intrinsic axial strain distribution of the REBCO layer for a 3 mm diameter central former, 4 mm tape width, and 45° winding angle.

Fig. 8. Intrinsic axial strain in the REBCO layer vs tape width for a 3 mm diameter central former CORC cable.

distributions of strain across the width of the tape under different winding angles are presented in Fig. 13.

From Fig. 13, it is clear that for winding angles ranging from zero to 60°, 45° is found to be the best configuration for winding. When the helix angle is further increased from 45° to 60°, the contribution due to twisting grows, increasing the strain. The strain across the width of the

tape is the least for the 45° winding angle. Van der Laan et al. [12] reported that the strain sensitivity is maximum when the strain is applied parallel to 0° ([100]) and 90° ([010]) directions. The critical current is independent of strain when the strain is applied at 45° ([011]) direction. The criteria used for the degradation of the superconducting layer is 0.45% axial tensile strain and -0.40% axial compressive strain [3,12]. At 0° winding angle, where the effect of twisting and thus torsion strain is the least, the distribution of strain is most uniform across the width, representing close to the pure bending strain. Eventually, it depends on the application and the anticipated bending radius of the CORC cable what the best choice would be for the winding angle.

4.3.3. Substrate thickness variation

Variation in thickness of the substrate used to make the superconducting tape affects the strain developed in the REBCO layer. When increasing the thickness of the substrate (made of Hastelloy), the relative position of the REBCO layer would move away from the central neutral axis. Therefore, while winding the intrinsic axial strain generated increases for a thicker substrate. The variation in the generation of strain with the decrease in thickness of the substrate is shown in Fig. 14 for different core diameters. It may be noted that the winding involves both the effects of bending and twisting in the tape. During the bending, compression is experienced in the layer below the neutral axis and tension in the layer above the neutral axis. The Fig. shows that when the thickness of Hastelloy is decreased, the compressive strain in the REBCO decreases for all core diameters. It may be also noted that the effect of decreasing the thickness of the substrate is more significant if the core diameter is small. An effective method to increase the critical current density is to decrease the total thickness of the wire, by using a thinner substrate. This will help in increasing the critical current density in the REBCO tape [22]. In 1 mm core diameter, the Hastelloy thickness decreases from 0.06 mm to 0.02 mm, the compressive strain decreases by 59%, and at 3 mm core diameter, it decreases by 44%. Comparing with the study in the literature [11], the results are having the same trend. However, the graphs of the previous work are steeper than those of the present one. That may be attributed to the difference in the modelling approach and the relaxation of homogenization.

4.3.4. Effect of tape width

The influence of tape width on the strain in the REBCO layer is investigated. The tape width is varied from 1 to 5 mm in 0.5 mm steps. The thickness of the Hastelloy substrate is 50 μ m and the copper stabilizer thickness is 20 μ m on both sides, while $\alpha = 45^\circ$. The results are depicted in Fig. 15, showing that the variation and distribution of strain generated are different for each tape width. Besides, a wavering strain pattern is observed. The reason for this pattern might be due to the

Fig. 9. Intrinsic axial strain pattern in the REBCO layer for different core diameters.

Fig. 10. Intrinsic axial strain of REBCO layer with different central former diameters.

Fig. 11. Maximum intrinsic axial compressive strain across the width of the REBCO layer with different central former diameter.

Fig. 12. Axial strain in the REBCO layer for different winding angles.

Fig. 13. Axial strain in the REBCO layer with different winding angles (central former diameter = 3 mm).

Fig. 14. Maximum axial tensile strain in the REBCO layer vs substrate thickness for different central former diameters from 1 to 3 mm and $\alpha = 45^\circ$.

Fig. 15. Axial strain distribution in REBCO layer for different tape width.

plastic deformation as observed in a long membrane. A possible explanation is that it may be a result of keeping the winding tension (improperly). Here winding tension is applied between 50 to 100 MPa based on the actual practice. Lin and Wickert [23] mentioned previously

that improper winding tension can lead to different defects in the tape related to both elastic and plastic deformation in REBCO tape.

The variation of the intrinsic strain in the REBCO layer across the width of the tape, for each tape width, is plotted in Fig. 16. It is observed

Fig. 16. Average axial strain in the REBCO layer vs tape thickness (central former diameter = 3 mm and $\alpha = 45^\circ$).

that when the tape width increases, the maximum strain generated decreases at the centre portion but the maximum value almost the same in all the cases.

It is understood that the warpage effect is more predominant in the small width tape, this is the reason for decreasing the compressive strain level with increasing the tape width. The maximum strain in the tapes remains on the same level for all tape widths.

The results obtained are in close agreement with the similar study reported in the literature [11]. Strain level in the superconducting layer decreases as the width of the tape increases. Additionally it is observed that, when the tape width increases, the maximum strain generated decreases at the centre portion but the maximum value is almost the same in all the cases.

4.3.5. Combined variation of copper, Hastelloy, and tape width

Fig. 17 depicts how the maximum compressive strain changes with variation of Hastelloy thickness from 0.05 to 0.02 mm at 0.02 mm copper thickness. And Fig. 18 depicts the variation of maximum compressive strain with the variation of Hastelloy thickness from 0.05 mm to 0.02 mm at 0.01 mm copper thickness. It may be noted that, as

the Hastelloy thickness increases, the compressive strain in the REBCO layer also increases. When the Hastelloy thickness decreases from 0.05 mm to a smaller thickness, the maximum strain value seems to converge towards a single point. It is also noted that the variation in maximum strain in the REBCO layer is higher for small core diameter. At 1 mm core diameter, the variation of maximum strain is 47 %, when the Hastelloy thickness decreases from 0.05 to 0.02 mm.

At 0.02 mm copper, and 0.05 mm Hastelloy thickness, 52% maximum strain variation is observed. A maximum variation of 43 % is observed when the core diameter increases from 1 to 3 mm, at 0.02 mm Hastelloy thickness. Similarly, at 0.01 mm copper thickness, and 0.05 mm Hastelloy thickness, 50% maximum strain variation is noted when the core diameter increases from 1 to 3 mm. It is obvious that these variations are larger at higher copper thickness.

So the model developed can assist in choosing optimized CORC parameters for different applications based on their requirements, the tape properties, and dimensions.

Fig. 17. Maximum intrinsic compressive strain in REBCO layer vs. Hastelloy thickness (0.02 mm copper thickness)

Fig. 18. Maximum intrinsic compressive strain in REBCO layer vs. Hastelloy thickness

5. Conclusion

Modelling of single layer REBCO tape has been carried out to characterize the degradation in superconducting behaviour for different winding patterns and tape parameters of CORC cable. Strain developed in the REBCO layer is due to the combined effect of axial tension, compression, bending, and torsion. The generation of strain under different conditions is calculated and compared to ensure that the strain remains within the degradation limits. Results show that the compressive strain in the REBCO layer increases with decreasing the central former diameter. The compressive strain in the superconducting tape decreases when the thickness of the substrate is decreased. It was found that 45° winding angle is the optimal angle for winding. The strain in the superconducting layer is decreasing with an increase of the tape width because the warpage in the tape due to twisting will be more significant on tapes with lesser width.

When the Hastelloy thickness decreases from 0.05 to 0.02 mm, at 1 mm core diameter, the variation of maximum strain is 47 % and 52%, at 0.01 and 0.02 copper thickness respectively. The compressive strain is increased by 43 % when the core diameter decreases from 3 to 1 mm, at 0.02 mm Hastelloy thickness. Similarly, at 0.01 mm copper thickness, and 0.05 mm Hastelloy thickness, 50% increase of compressive strain is noted when the core diameter decreases from 3 to 1 mm.

Declaration of Competing Interest

None.

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