Influence of local deformation on critical current of high temperature superconductor tape

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Abstract. In many applications, high temperature superconductor (HTS) tapes are placed on top of uneven surfaces. Because the electrical properties of HTS tapes are sensitive to mechanical loading, mechanical stress generated at such local imperfections can considerably decrease the critical current of a HTS tape. Then a method of predicting degradation of critical current from a numerical simulation would be helpful.

We present the results of 3D mechanical finite element model analysis, using the software ANSYS for optimising the geometry of a round CORT (Conductor-On-Round-Tube) cable. In these simulations, the HTS tape is bent around a circular former of certain diameter with a surface imperfection. We used three parameters to characterize the imperfection geometry: diameter of the former, the height and the width of imperfection. In order to validate the mechanical simulation results, we performed in-situ measurement of critical current of HTS tape.

1. Introduction
Electrical properties of high temperature superconducting (HTS) tapes such as REBCO, are sensitive to mechanical loading. Because of that, investigation of impact of mechanical loading on these properties is needed. The most straightforward way are experimental measurements, where this dependence is directly measured. In order to reduce the expenses of such investigation, the measurements are to be complemented by analytical calculations or for more complex cases by numerical simulations. We constructed device for manufacturing of double layer cable from helically wound HTS REBCO tapes, which can be seen in Figure 1 [2]. Multiple short samples were made, on which we learned how to make a cable without damaging the tapes.

Figure 1. Machine for cable production
We investigated samples tested under various loads to find out how they were damaged. We noticed that the edges of the first layer of the wound cable impressed into the second layer in some places, which lead to increase of local mechanical loading and consequently to reduction of electrical properties of the cable. The tape in figure 2 is damaged in this way. To prevent this damage, we decided to develop a method for evaluation of global mechanical loading and local mechanical loading.

Global mechanical loading is meant in this article as loading due to simple bending of tape around the former of CORC cable. Local mechanical loading is meant as bending of tape around former, which has surface imperfection (SI) on the surface of the former, which leads to increase or decrease of strain of the tape at the area of the SI.

![Figure 2. Damaged tape (top) due to the raised edge of the first layer (bottom)](image)

2. Measurements setup

For experimental measurements, we designed and manufactured a device for in-situ measurements of dependence of critical current on mechanical loading during bending of HTS tapes, presented in figure 4. We measure this dependence, when the tape is bent around a circular tip. By making small adjustment, we can create small irregularity on top of the tip and study the influence of resulting local deformation due to the SI.

REBCO tape, bought from Superpower Inc. [3], is soldered onto current leads. The structure of this tape can be seen in figure 3. On the side closer to REBCO layer voltage taps are soldered. Tape is then put under tension by two small weights, both 0,34 kg heavy, in the way, that it doesn’t warp. Device is then submerged into liquid nitrogen and we measure critical current of the tape, while ramping up DC slowly and detecting electric field. We use 5 µV/cm threshold, in order to identify clearly the appearance of signal from noise present during measurements.

![Figure 3. Geometry of HTS tape SCS 4050[3]](image)
Afterwards, we insert into the device the loading bar, equipped with the pressing head, which has circular tip at its end, around which the tape is bent. We put weight on top of the loading bar, and we determine the critical current. This procedure is repeated for a set of loads increasing monotonically.

![Device for in-situ measurement of Ic – F1 dependence](image)

**Figure 4.** Device for in-situ measurement of $I_c$ – $F_1$ dependence

### 3. Calculations

It is common to present the mechanical loading of HTS tapes in terms of strain, which is in fact the comparison between the initial state of a body and the deformed state of a body due to applied force. We used analytical calculations for simple bending, which we use for validation of our method. Then, for more complex configurations, we use numerical calculations.

#### 3.1 Analytical calculations

Strain present in the superconducting layer, during simple bending, can be simply calculated as difference between the circumference of neutral line (zero strain) and of the superconducting layer. If we consider only the materials with highest volume fraction and the superconducting layer, we can calculate the strain in the way presented in figure 5.

![Analytical calculations of strain during simple bending of REBCO tape](image)

**Figure 5.** Analytical calculations of strain during simple bending of REBCO tape

\[
\varepsilon = \frac{C_R - C_r}{C_r}
\]

\[
\varepsilon = -\frac{x + 2u}{d + x + 2t + 2u}
\]

#### 3.2 Numerical calculations

Numerical calculations are done in the Workbench module of software ANSYS. Material data were used as published by the manufacturer in figure 6 [4]. The REBCO tape is modelled as four layers composite, as can be seen in figure 7.
Figure 6. Material data of REBCO tape

Figure 7. Numerical model of REBCO tape

We developed two 3D models – Model A for case with 6 mm pressing head and Model B with SI on top of the pressing head.

3.2.1 Model A. This model, presented in figure 8, is used for the case of simple bending. It is also used for validation of our method presented in this study. Tape is modelled as four layers composite, where each layer is modelled as solid (SOLID186) and is bonded to each other. Tape is bent around circular tip, which is being pressed into the tape by increasingly higher load $F_1$. Tape is kept in tension, so it doesn’t warp at the beginning by force $F_2$. Between the tip and tape is frictional connection. The REBCO layer has 2 elements across the thickness and 14 elements across the width. The evaluated mechanical load is characterized by the highest value of compressive principal strain occurring in the REBCO layer, which can be seen in figure 9.

3.2.2 Model B. This model is the modification of model A (figure 10.), when on the surface is now present a surface imperfection (SI). This model is used for investigation of local deformations, where the tape bends around the SI and the resulting strain is affected, at the area of the SI, by this geometric feature. The SI models the situation, where in a REBCO cable, inner layer tapes press into the outer layer tapes. The SI is modelled perpendicular to the tape length. We consider the height of the SI between 0 – 300 µm and the arc length of the SI between 0,5 mm – 6 mm. The evaluated mechanical
load is presented as the highest value compressive principal strain occurring in the REBCO layer (figure 11).

3.2.3 Comparison between analytical calculation and numerical calculations of model A. As first benchmark of the numerical model we compared it with analytical calculations of simple bending case presented in section 3.1. The results of these comparison can be seen in figure 12.

|               | Strain Analytical | Strain Numerical |
|---------------|-------------------|------------------|
| 2 mm former   | -0.02578          | -0.02703         |
| 4 mm former   | -0.01319          | -0.01383         |
| 6 mm former   | -0.00886          | -0.00921         |

Figure 12. Comparison of numerical results of model A and analytical calculations

We see difference between the values, which increases with strain, however the trend is the same and difference is still small, so we consider this as a good agreement between the methods. The difference can be explained by the fact, that the numerical calculation considers also a change of the stiffness of the materials, which in this case leads to higher strain.

3.2.4 Results of numerical simulations – Model B. We can compare the results from model A and model B and obtain in this way a better understanding of how much will such SI increase the local deformation. We selected dimensions according to the cable production process. The diameter of the pressing head is 6 mm and the SI is 0.09 mm tall and 1 mm wide.
As we can see from figure 13., the maximum value of compressive strain is increased by 20% due to the surface irregularity. When we reduce the width of the surface irregularity, it acts more and more as a cutting edge and the resulting strain is even higher. We can see that the initial slope of the curves is different, which is due to the fact, that at the beginning, when there is SI, the bending diameter is bigger, so the strain is smaller. Then the peak is reached at point, where the bending diameter is equal to the former diameter. At this point the tape starts to envelop the former and the strains starts to decrease. This is due to the fact, that the angle at which the force is applied starts to change from bending behaviour to tensioning behaviour, which leads to decrease of the compressive strain. Considering this, the surface should be made as even as possible, presumably by increasing the height of rest of the surface to the same height as is the surface irregularity.

4. Results and validation of method

To validate the method presented in this work, we made experimental measurements to compare with the predictions of numerical calculations. To compare measurements and numerical calculations and to have a benchmark, we used published data of dependence of electrical properties of YBCO and GdBCO tapes on strain, which can be seen in figure 14 [1].

Figure 13. Maximum value of compressive principal strain during bending computed by models A and B, respectively

Figure 14. Strain dependence of commercial HTS REBCO tape [1]
From these data, we calculated the reduction of critical current at specific load values. In this way, we can directly compare the results of our measurements and calculations.

![Graph](image1)

**Figure 15. 6 mm pressing head – numerical and experimental data**

We did measurements for two cases. First one is the same as Model A, with 6 mm pressing head, with even surface, which can be seen in figure 15. In figure 16 is the second one, which is the same as Model B and has the surface irregularity on top of pressing head, which has 6 mm diameter. The surface irregularity is 0.09 mm tall and 1 mm wide.

![Graph](image2)

**Figure 16. 6 mm pressing head with surface irregularity – numerical and experimental data**

We can see from figures 15 and 16 that numerical data and data from experiments are in fair agreement assuming the properties of GdBCO superconductor. First, there is a sharp reduction of critical current, which is due to the bending of the tape around the pressing head. According to the numerical calculations, when the tape reaches the bending radius of 3 mm, the strain no longer increases at the peak point but starts to distribute evenly around the circumference of the pressing head. This is presented in figure 17. Due to the way the measurement is set up, when the tape envelops the pressing head, it assumes U shape and the loading changes from bending to tension, which explains the increase of critical current seen in both numerical and measurements results. The local increase of strain due to the uneven surface reduced the critical current of the tape by about 10%. 
Figure 17. Distribution of strain along the length of the tape at different specific loads – Model A

5. Conclusion

We explored a possible mechanism behind the damage of the second layer of helically wound tapes in the cable, assuming it is caused by the first layer of tapes. In particular, we investigate how the edges of tapes in the first layer could be elevated creating an uneven surface, on which the second layer is wound. The model was utilized for predicting how this mechanism will affect electrical properties of HTS tape during bending of tapes around such an uneven surface. As a result, we have achieved understanding of how the mechanical loading affects the tapes during cable production. We found that surface irregularity with the specified dimensions increased the strain locally by 20%, in addition to the strain present during the bending, which leads to an additional decrease of critical current (about 10%). We will also use these findings in the cable production, with the aim of increasing the reliability of production and reducing the material costs.

References

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