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Dissertation Thesis Abstract

Influence of mechanical deformation on the electrical properties of high-temperature superconductor tapes

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1. Introduction

Superconductors are a new type of electrical conductors, which need to be cooled to very low temperatures (< 77 K), where they exhibit very good electrical properties. These conductors enabled constructions of devices, which were previously considered very complex or impossible to build. Devices, such as European Organization's Nuclear Research Large Hadron Collider (particle accelerator) or International Thermonuclear Experimental Reactor (nuclear fusion reactor), would be too inefficient or too big to be viable. To implement superconductors into more common devices, where the electrical advantages of using superconductors are not so pronounced, more optimization is needed. Not only by trying to find materials, which are superconducting at higher temperatures, but also a better understanding of existing superconductors is needed.

All superconductors are divided into two categories by their response to external magnetic field – type I and type II. Type II superconductors are the only used industrial superconductors and are further divided into two categories. First are the low temperature superconductors, which are commonly cooled by liquid helium (4.2 K), such as Niobium-tin (Nb3Sn) [1] and Niobium-titanium (NbTi) [2]. Second category are the high temperature superconductors (< 77K), specifically Bismuth Strontium Calcium Copper Oxide (BSCCO) 2212 and 2223 [3], and Rare-earth Barium Copper Oxide (REBCO) [4]. High temperature superconductors were discovered around 30 years ago and research on them is far from finished. Progressing rapidly is the technology of producing so called superconducting tapes or coated conductors (CC) containing thin (few μm) REBCO layer on a 50-100 μm metallic substrate (Hastelloy, stainless steel, NiW) surrounded by a protective 5-20 μm thick high-conductivity metal (Cu, Ag) layer.

The principal motivation of this thesis was a national project concerned with the construction of a superconducting coil using a cable, which was made from superconducting tapes (coated conductors). In order to achieve the round form of the cable, the conductors are wrapped in a helical manner around a Cu tube. Advantage of this Conductor-On-Round-Tube concept is the possibility to cool the coil by forced flow of liquid nitrogen through the central tube. During preliminary tests, a line-like deformations were observed on the conductor surface. The existence of such deformations was reported in publications, however their impact was not explored. This motivated us to investigate thoroughly this issue.

This thesis is focused on the mechanical deformation of coated conductors when assembled into round cables. A common way to characterize the importance of mechanical properties is to measure the change of critical current, when a coated conductor is under mechanical loading (axial, compressive, transverse). The mechanical limits of coated conductors were established as critical strain (or stress) limit ε_{cr} and irreversible strain (or stress) limit ε_i . The irreversible strain limit was established as a value of strain, when the critical current of a coated conductor irreversibly lowers by 1%.

The critical strain limit was established as a value of strain, when the critical current reversibly lowers by 5%.

2. Transporting capability of coated conductors (superconducting tapes) assembled in a cable

As part of the national project, mentioned in the Introduction, a two-layer Conductor on Round Tube (CORT) sample cable was prepared by hand. A study was conducted to investigate the impact of helical placing of coated conductors on a circular former. A degradation of the critical current of coated conductors was observed. In CORT cables and in all investigations in this thesis, coated conductors are placed with the superconducting layer closer to the tube, because the dependence of the electrical properties of coated conductors are generally less affected by compressive mechanical loading.

An experimental test was conducted, where a single coated conductor was wound around a circular former at 45º angle. The critical current was measured and varied from the lowest value of 105 A to 200 A. We assumed, that the distinct fluctuation of the coated conductor critical current is caused by bending it around the circular former. The bending either created microcracks in the superconducting layer or enhanced existing microcracks. However, the exact dependence and cause between the degradation of the critical current and parameters of the bending (radius of the former, angle of the conductor placing), was not fully explained.

We are convinced that thorough characterization of the mechanical and electrical properties of REBCO coated conductors, when subjected to a mechanical loading, is very important to ensure the required properties of devices, such as high field magnets. In this thesis, we aimed to address two main problems – characterization of the electrical properties of coated conductors when bending over smooth circular surface and the impact of introducing a line-like surface irregularity (SI) on a circular former on the resulting electrical properties of a coated conductor.

The line-like deformations were observed on coated conductors used in short cable samples prepared by hand (Fig. 1). In these samples, the inner and outer layer had different winding direction, and the inner superconductor was pressing into the outer conductor. In some cases, the critical current of these conductors lowered to zero and only the metallic parts conducted the electrical current. Similar deformations were reported on in [5]. These were caused by the underlying conductor edges, pressing into the conductor in the following layer. However, no in-depth studies of the risks these deformations present and how to potentially mitigate them, were not done at the time.

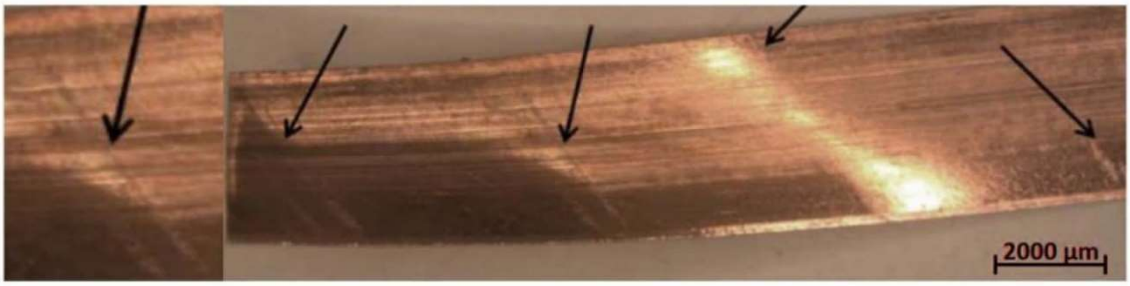


Figure 1. Line-like deformations on the inner face of a coated conductor from the second layer of a CORT cable [6]

Several articles were published, where the effects of these deformations can be seen [7,8]. When the coated conductors are crossing, the tape is damaged perpendicular to the tape length (Fig 2 b). In this case, if the thin superconducting layer breaks across the width, the electrical current cannot pass. If we change the cable design, so that superconductor layers are placed with the same direction, the line-like deformations would be oriented along the conductor length (Fig 2 a). This way the deformations are along the conductor length and should hinder current flow less than if they are perpendicular.

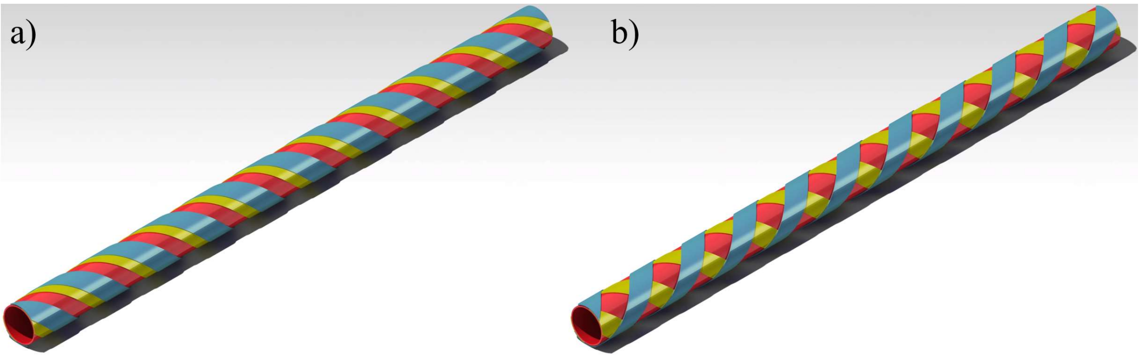


Figure 2. A CORT cable with coated conductors laid: a) with the same orientation b) with opposite orientation

The introduced tasks were addressed by multiple methods in this thesis. Numerical calculations were made for both the parallel (Fig. 2 a) and the perpendicular (Fig, 2 b) surface irregularity. Analytical solution for evaluating the strain caused by the line-like surface irregularity was proposed. The results were validated by measurements and comparison of bending a coated conductor over a smooth circular former and a circular former with surface irregularity was done.

3. Superconducting coil produced from 40 m long CORT cable

The research presented in this thesis is related to the national project financially supported by Slovak Research and Development Agency. The goal of this project was to develop a device for construction of long-length CORC/CORT cables, production of two-layer 40 m long CORC cable and finally construction of a solenoid from the cable and characterization of the solenoid. The accomplishments of this project were reported in [9].

After tests on small cable samples, it was decided to wind both layers with the same sense of the lay angle, so that the conductor edges from the first layer push in parallel direction into the conductors in second layer. The conductors were oriented with superconducting layer closer to the former, to ensure its compressive loading. The total possible current of the cable (summation of the critical current of each coated conductor) was 1240 A. A cabling machine was designed and constructed (Fig. 3). The produced 40 m long CORT cable was then used to make a superconducting solenoid. The solenoid has 4 layers, each containing 20 turns.

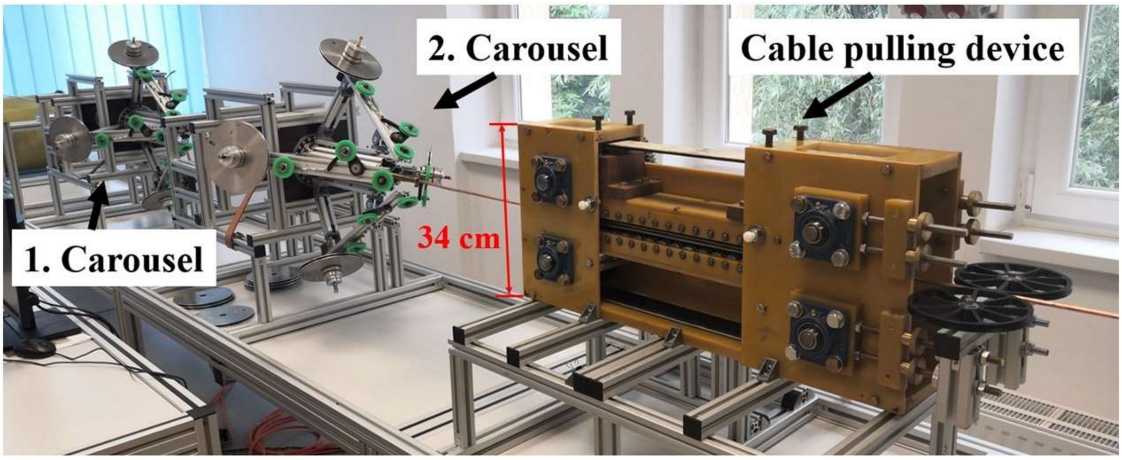


Figure 3. CORC/CORT cabling machine [6]

The produced 40 m cable was used as a basis for further studies. The parameters set during the cable production were used as input data for calculations: the force keeping the coated conductors in tension (to prevent warping), winding angle at which the tapes were wound onto the former with specific diameter and lastly the former pulling speed.

4. State of the art - summary

Recent publications concerning the electrical properties of coated conductors are mostly targeted at the specific tasks, which the groups are working on. The published data in most cases are either of an experimental nature or concern the electrical properties of coated conductors under global mechanical loading conditions (e.g. only tensile test). The intricacies are explored less in publications, and if they present a problem, instead of fully exploring the impact they have on the specific application, a provisional solution is suggested or applied. The line-like deformations present a general problem and are not limited on the specific case of a round cable that motivated this thesis.

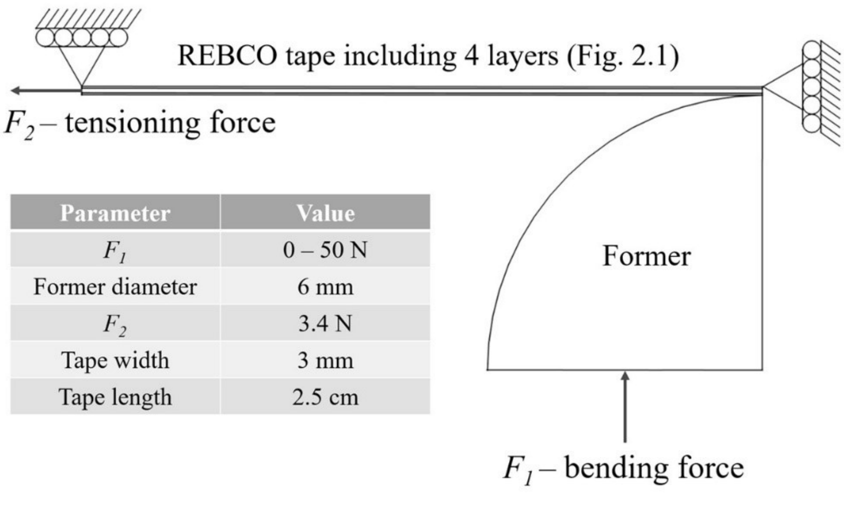
5. Theoretical and experimental methods used for investigating the bending of coated conductors over a smooth circular former

The compressive strain of a simply bent coated conductors or bent conductors in a CORT cable can be characterized by comparison of the undeformed and the deformed shapes. Analytical method for calculation of the compressive strain in the superconducting layer of a coated conductor bending over a smooth surface were already used by research teams in the past. The strain ε can be characterized as

$$\varepsilon_{compressive} = -\frac{h_{REBCO} + \left(\frac{h_{hastelloy}}{2} - h_{comp}\right)}{R_{core} + h_{MC}} \qquad (1.)$$

where R is the radius of a cable core and h is thickness of constituent layers. Because the coated conductor is not symmetrical, the centroid is shifted. The thickness h_{MC} is distance of the centroid of a coated conductor from the surface of outer layer, which is closer to the former.

We made two numerical models for characterization of the mechanical properties of the coated conductor SCS3050 during bending over a smooth circular former. First model is used for the evaluation of compressive strain in the superconducting layer, when a coated conductor is bending over a smooth circular former, which can represent loading conditions the coated conductor experiences, when it is placed on the former in CORC/T cable (Fig. 4). Second model is a variant of the first model used to investigate, how the change of an angle between a former and a conductor affects the compressive strain in the superconducting layer occurring during bending of a coated conductor over a circular former.



Parameter	Value
F_1	0 – 50 N
Former diameter	6 mm
F_2	3.4 N
Tape width	3 mm
Tape length	2.5 cm

Figure 4. Smooth surface numerical model

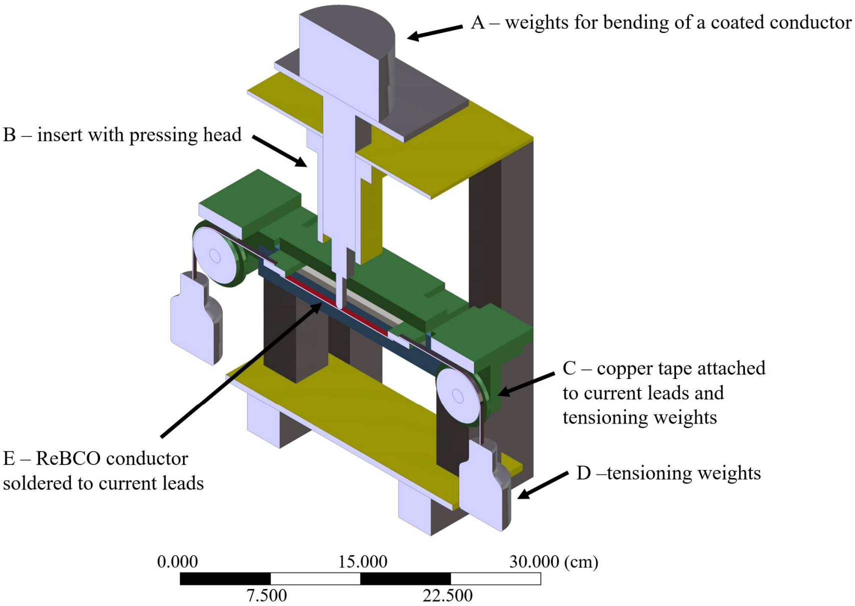


Figure 5. In-situ three-point bending measurement device: A – weights for bending of conductor, B – insert with pressing head, C – pulleys with a copper tape attached to current leads from opposite side, D – tensioning weights, E – a coated conductor attached to current leads [6]

Validation of the numerical and the analytical calculations is done using three measurement methods. At the time of writing this thesis, two of the three measurement methods allow direct measurement of the critical current degradation of coated conductors [10 - 12]. First method is a variant of the three-point bending test (Fig. 5). It is used for measurement of the critical current of a coated conductor in a liquid nitrogen bath, in which a pressing head with a circular tip is pushed into the coated conductor sample. In the second measurement method, the sample is bent around a circular former at 45° angle and then submerged into a liquid nitrogen bath (Fig. 6). The diameter of the circular former used for bending of the coated conductor can be adjusted.

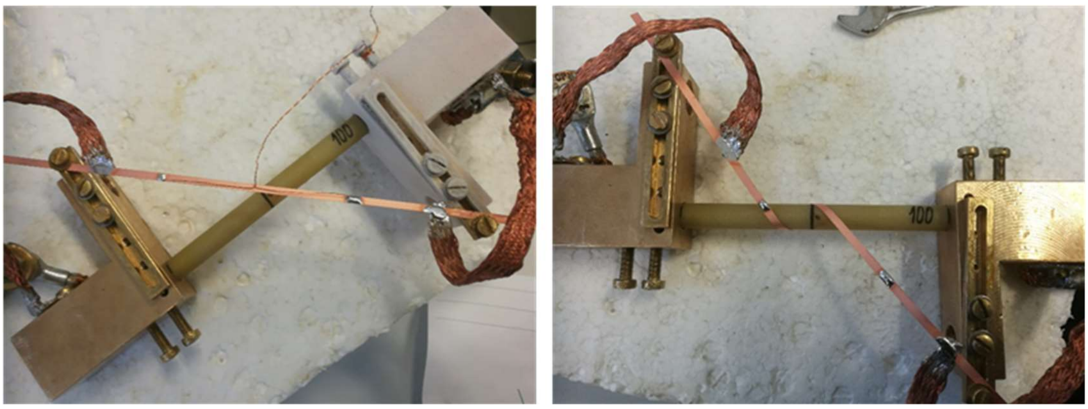


Figure 6. Device for in-situ measurement of the critical current of a bent conductor around a specific former at 45º angle

The third utilized method is Digital Image Correlation (DIC) method. It is a non-contact optical measurement of a deformation in real-time. The method uses high-resolution high-speed cameras to capture in real-time the deformation of a body or to capture detailed pre-deformation and post-deformation images of a body subjected to a mechanical loading. The measurements were done in collaboration with Faculty of Engineering of Slovak University of Technology in Bratislava.

6. Origin of the line-like deformation

The line-like deformations present a legitimate concern. Up till now, the potential damage they can cause in superconducting devices was not directly addressed, and instead was only mitigated. However, this can later lead to unconsidered problems, such as during cyclic operation, the additional local strain can lead to a propagation of microcracks, and destruction of the superconducting device. The line-like deformations are most notable on the inner face of a coated conductor in the second and in the subsequent layers in CORC/T cables, where each layer is placed with a different winding direction. These deformations occur at places, where the coated conductors touch each other between the layers. We believe a proper understanding of the impact these line-like deformations can cause is very important.

When the coated conductor is bent around the former, a supplementary deformation occurs. Because half of the conductor is in tension and half is in compression, the cross section has to further deform to complement the principal deformation. The supplementary deformation raises the edges of the cross-section resulting in a U shape of the cross-section. This supplementary deformation is called Poisson's effect and is characterized by the material property named as the Poisson's ratio. Unfortunately, it will be always present, and we can only try to mitigate the effects it brings. That is why it is important to understand, to what degree it can increase or decrease the local strain at the points where the conductor edges cross.

7. Theoretical and experimental methods used for investigating the bending of coated conductors over a non-smooth circular former

The line-like deformation is a supplementary deformation caused by the Poisson effect during bending of the coated conductor. The resulting deformation can be approximated by introducing an irregularity on the surface of a circular former. The surface irregularity represents a surface roughness or the edges of coated conductors in a previous CORC/T cable layer. Analytical solution to this problem was suggested. The coated conductor bends around the corner of the surface irregularity at a reduced bending radius (Fig 7.). The reduced bending radius can be characterized as

$$R_b = R_F + h - \frac{h}{\left(1 - \sin\theta_{ef}\sin\theta_T - \cos\theta_{ef}\cos\theta_T\right)} \tag{2.}$$

Afterwards, we can evaluate the resulting maximum compressive strain as

$$\varepsilon_c = \frac{\frac{h_{HASTELLOY}}{2} + h_{REBCO} + h_{COPPER}}{R_b} \tag{3.}$$

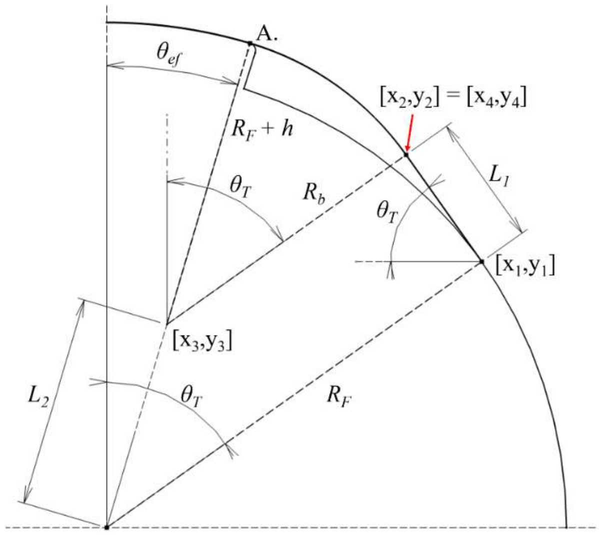


Figure 7. Geometrical parameters for evaluation of the compressive strain caused by the SI

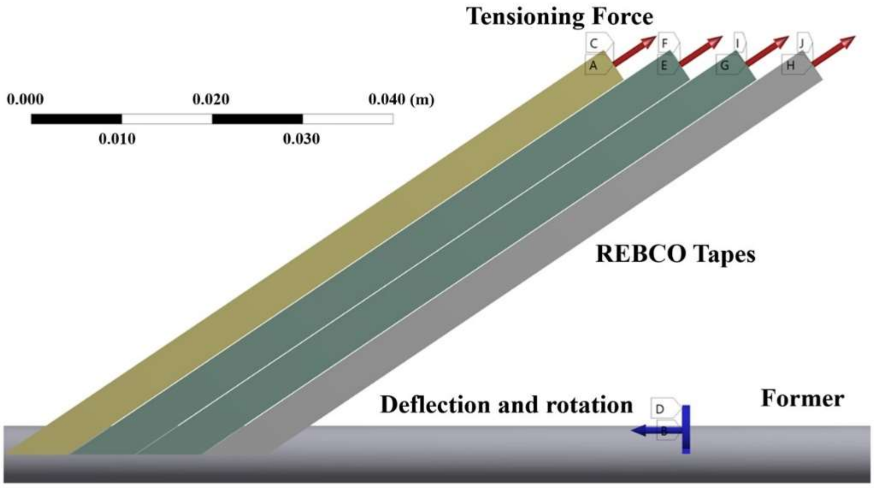


Figure 8. Numerical cable production model [6]

The numerical calculations of the compressive strain are performed using two distinct numerical models. The first model is an approximation of the CORC/CORT cable production process, from which we evaluate the approximate height of the raised edges for further calculations, both numerical and analytical (Fig. 8). The second model is a variant of the model from Figure 4., where on top of the former is added a perpendicular or parallel surface irregularity.

8 Results – a coated conductor bending over a smooth and non-a smooth surface

First are shown the results of bending a coated conductor over a smooth circular former. The results of analytical and numerical calculations and validation measurements are listed and explained. Afterwards, the situation of a coated conductor bending over circular former with a parallel and a perpendicular surface irregularity is explored. Differences between the numerical and the analytical results are explained, and validation of numerical results is given.

We look at the simple bending situation, which corresponds to the case, when the conductor in the first layer is wrapped around the circular former in a CORC/CORT cable. In the cable structure, the former radius and substrate thickness are the largest dimensions present in the equation. By adjusting the radius and the substrate thickness, we can significantly lower the compressive strain affecting the superconducting layer (Fig 9.).

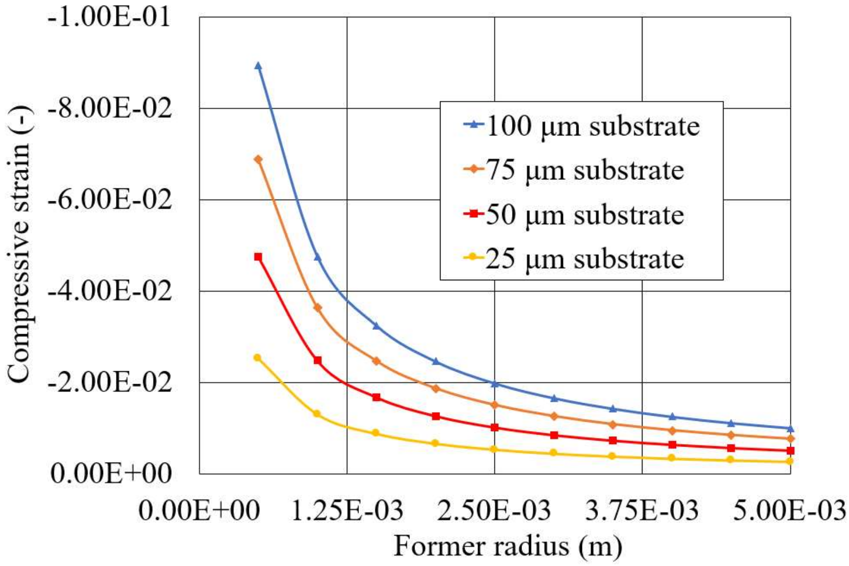


Figure 9. Influence of the former radius and the substrate thickness on evolution of the compressive strain in the superconducting layer (symmetric 20 μm thick stabilizing copper layers)

We considered adjustment of the copper layer thickness to push the neutral line closer to the REBCO layer, therefore lowering the compressive strain almost to zero. It could be achieved by the addition of copper to one side of the coated conductor. Rough approximation of the required thickness can be calculated using the rule of mixture, meaning that stress acting on the copper cross section is equal to the stress acting on the Hastelloy cross section. However, this would lead to very thick copper layer, because the mechanical strength of Hastelloy is more than double the mechanical strength of the copper. Instead, we could laminate higher mechanical strength material on top of the copper layer. Still, this would prevent lowering of the bending diameter of a cable and reducing the current density of a cable.

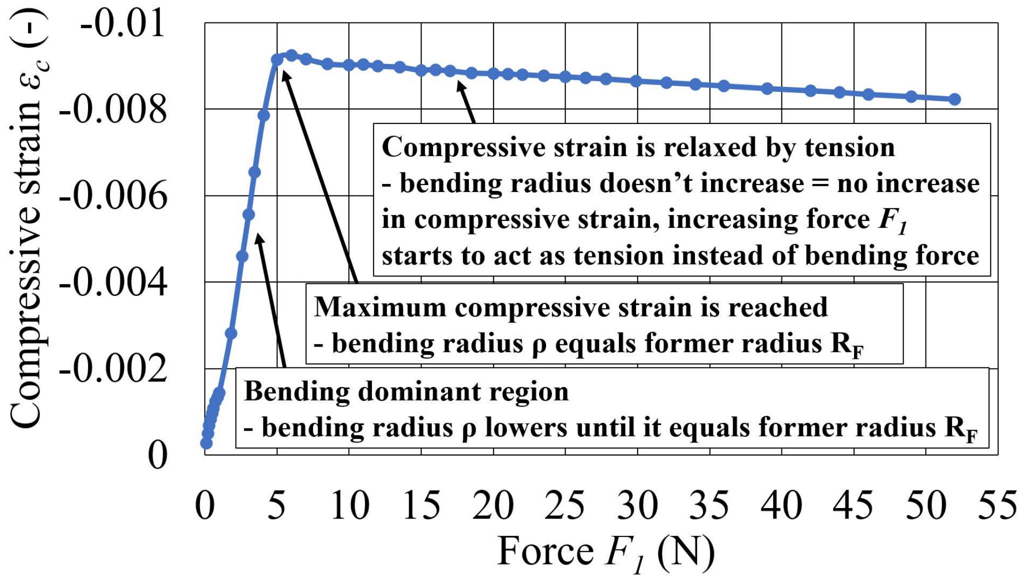


Figure 10. Maximum compressive strain in the REBCO layer bent around a smooth 6 mm former calculated from the smooth surface numerical model [6]

The numerical model of one coated conductor bending over a smooth circular former shows the impact of the former radius on the compressive strain in the superconducting layer. We compared the results of numerical calculations of the reference case of smooth surface model with the analytical calculation from Section 5.1, which can be seen in Table 1. There is a good agreement between the methods.

Table 1. Maximum strain in the REBCO layer of a bent coated conductor - comparison of the results of numerical and analytical calculations

Former diameter (mm)	Strain ε_c Analytical (-)	Strain ε_c Numerical (-)
2 mm former	-0.02578	-0.02703
4 mm former	-0.01319	-0.01383
6 mm former	-0.00886	-0.00921

Measurements, with the same conditions as in the numerical and analytical calculations, were prepared for the validation of the results (Fig. 11). The comparison is indirect, because we measured the decrease of the critical current of the coated conductor SCS3050 when the bending force is increasing. However, we can observe a similar behaviour as in Figure 10. When we look at the published data, we can calculate the expected decrease of the critical current caused by a specific amount of the compressive strain, which we can directly compare with our measurements. We see from Table 2. that there is good quantitative agreement.

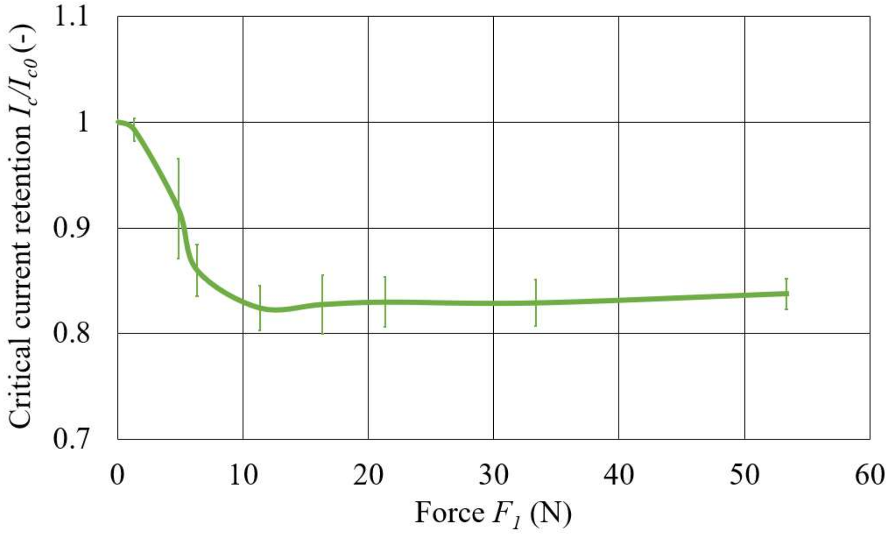
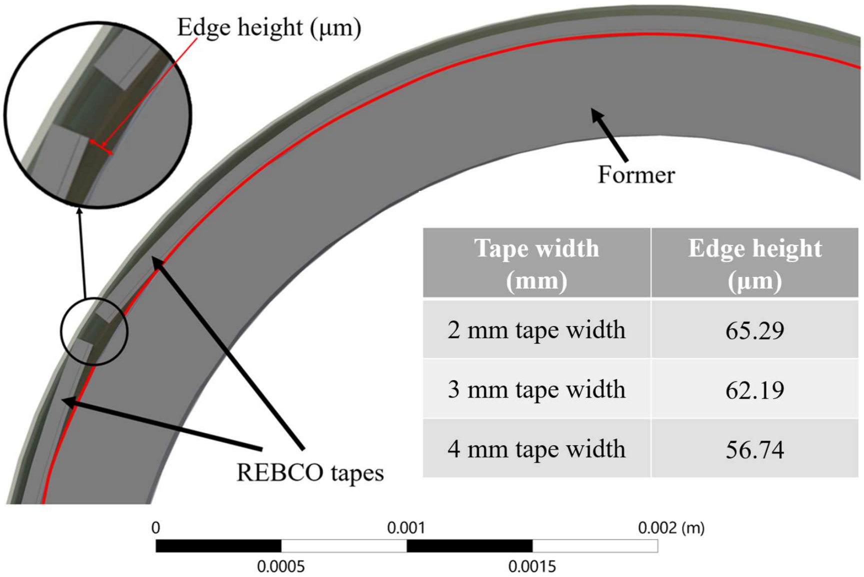


Figure 11. Retention of the critical current during bending of the coated conductor SCS3050 over 6 mm smooth circular former

Table 2. Comparison of the predicted and the measured decrease of critical current of coated conductor bent over a smooth circular former

6 mm bending head	Predicted I_c reduction	Measured I_c reduction
Without SI	18.3 %	17.5%

We presented numerical methods for the evaluation of the impact of line-like deformations. The cable winding model provides prediction of the height of the bent coated conductor edges. The second numerical model is used to calculate the maximum compressive strain in the superconducting layer of a coated conductor bent over a circular former with a surface irregularity – parallel and perpendicular. The calculated height of the edges of the bent coated conductors are less than 100 μm for the values of parameters used to produce the 40 m superconducting coil (Fig. 12). However, for the numerical and the analytical calculations in Section 5.5.2 and 5.6, we increased the possible edge height up to 700 μm to investigate larger set of possible configurations.



Tape width (mm)	Edge height (μm)
2 mm tape width	65.29
3 mm tape width	62.19
4 mm tape width	56.74

Figure 12. The cross-section of a single layer of conductor laid helically at the angle of 34 degrees on a round former with 6 mm diameter [6]

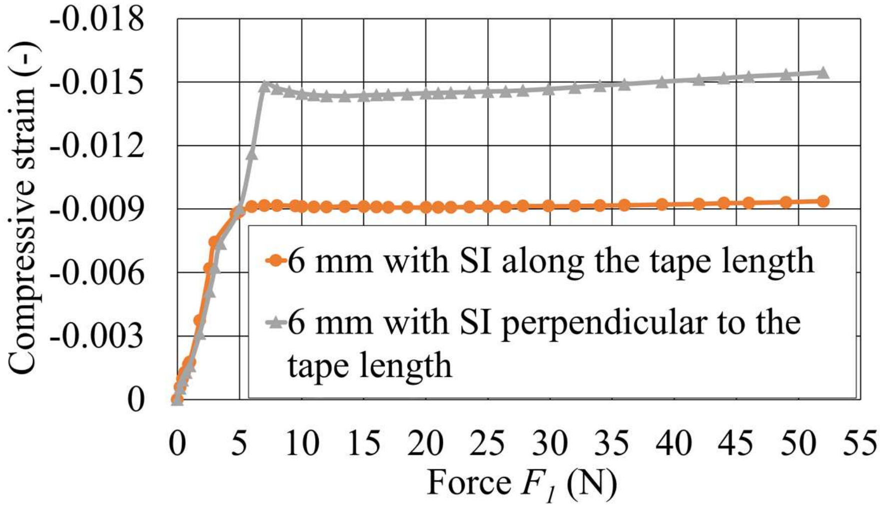


Figure 13. Comparison of maximum compressive strain in REBCO layer evaluated by numerical calculations

The numerical models of one coated conductor bending over a circular former with a surface irregularity – either parallel or perpendicular, are used to evaluate the local impact of the line-like deformations. The highest compressive strain in the superconducting layer of the coated conductor was caused by the perpendicular surface irregularity (Fig. 13). The high local strain certainly explains the existence of the line-like deformations in CORC/T cables, where the subsequent layers of coated conductors are placed with the opposite orientation.

The maximum local compressive strain caused by the parallel surface irregularity is the same, as for bending of a coated conductor around a smooth circular former. However, from Figure 5.13, we see that the distribution of the compressive strain in the superconducting layer is not monotonic. We observed a similar behaviour in experimental measurements.

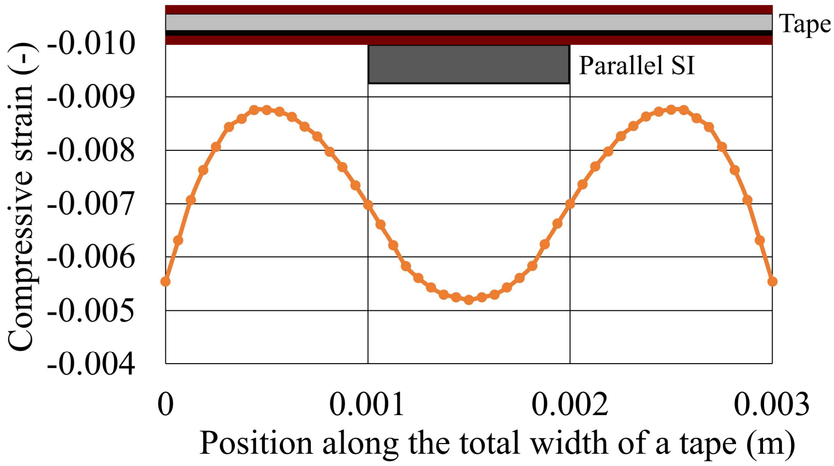


Figure 14. Distribution of the strain in REBCO layer, when the maximum compressive strain is present, across the coated conductor width for a SI parallel to conductor length - obtained from the parallel SI numerical model [6]

Analytical solution for the evaluation of compressive strain in the superconducting layer of a bent coated conductor were proposed. The calculations were conducted for a wide range of values of the height and the arc length of the surface irregularity. Two coated conductor lengths were considered in the calculations – 1 m and 4.94 mm

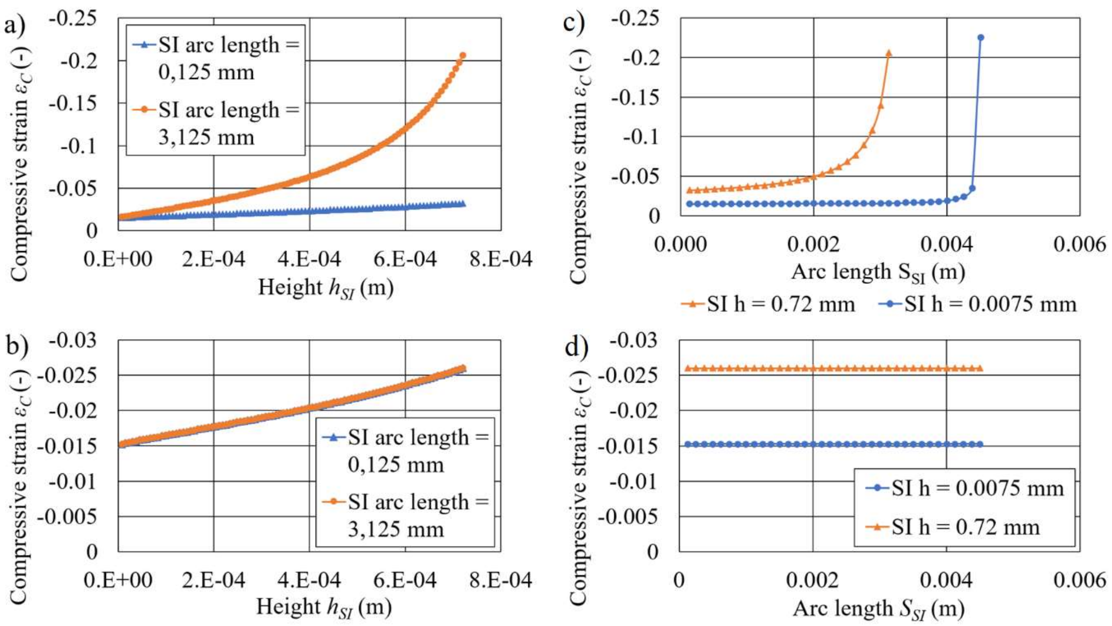


Figure 15. Influence of the height and the arc length of the SI on the maximum compressive strain in REBCO layer – a) for L = 4.94 mm, b) for L = 1 m [6]

The results of the numerical and analytical computations were compared for the case of a coated conductor bending over a circular former with a perpendicular surface irregularity. The same material model was used for both calculation methods. The discrepancy between the results is caused by the different deformation behaviour considered in the calculation methods. The deformation behaviour assumed in the analytical calculations is more rigid compared to the numerical method. The results for the compressive strain dependence on the surface irregularity arc length show the worst qualitative agreement (Fig. 16 b blue and orange line). When the boundary conditions of the numerical model are modified to be similar to the one used in analytical calculations (Fig. 16 b), we achieve better qualitative agreement between the methods (Fig. 16 b green line).

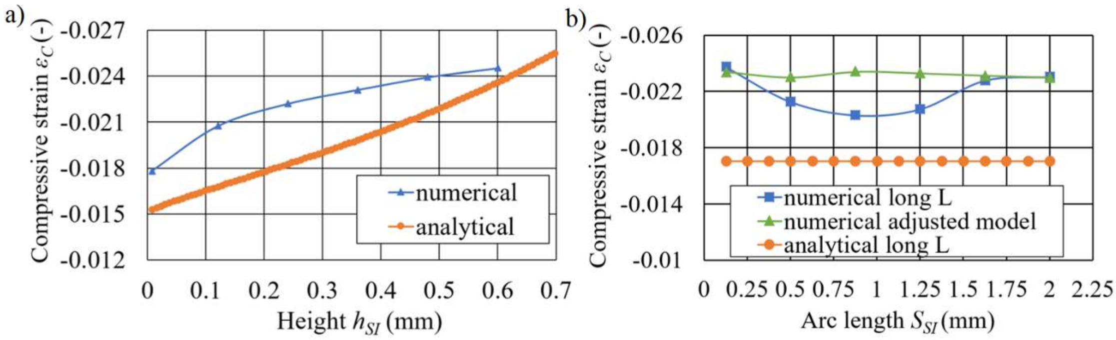


Figure 16. Dependence of the maximum compressive strain in the REBCO layer on a SI a) height and b) arc length [6]

The analytical calculations in combination with the numerical calculations provide good insight into the impact of parameters of the surface irregularity on the maximum local compressive strain in the superconducting layer of a coated conductor. Superconducting devices require reliability and using the higher values of compressive strain from numerical calculations provide a more conservative approach. The numerical calculations were validated using measurements and provide good prediction of the actual strain caused by the bending of the coated conductor over a surface irregularity resembling line-like deformation.

Measurements were done on the in-situ three-point bending devices. At the tip of the pressing head was attached a surface irregularity resembling the line-like deformation. We observe similar behaviour as we can see in the numerical calculations (Fig. 13). Perpendicular surface irregularity has much more severe impact on the critical current of the coated conductor compared to a parallel surface irregularity (Fig. 17). If we take into account the published data on critical current degradation due to a compressive strain, we can compare the critical current degradation predicted by the numerical calculations and the measured degradation (Table 3.).

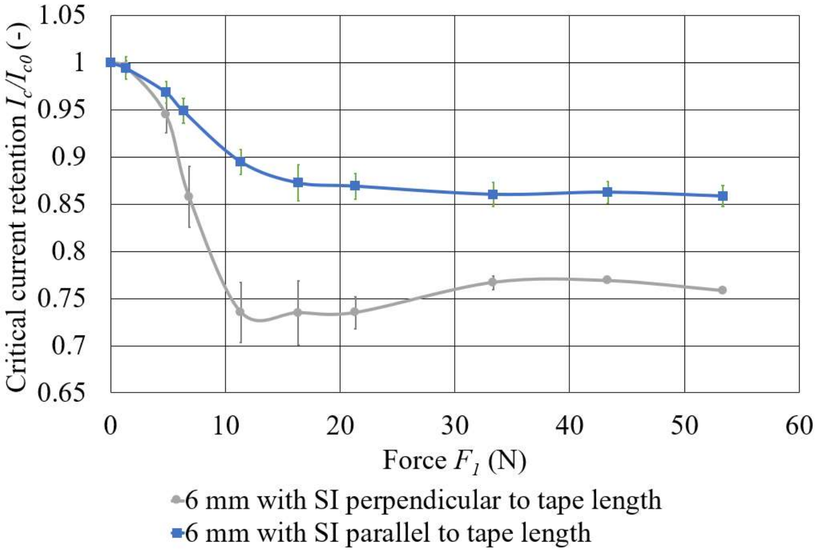


Figure 17. Impact of the parallel and the perpendicular SI on the degradation of critical current of the coated conductor SCS3050

Table 3. Comparison of the predicted and the measured decrease of critical current of a coated conductor bent over a circular former with a perpendicular surface irregularity

6 mm bending head	Predicted I_c reduction	Measured I_c reduction
With ⊥ SI	33.5%	26.5%

9. Conclusions

In this work a thorough methodology for investigation of the electrical properties of coated conductor when bent around a smooth and a non-smooth circular former was proposed. Analytical, numerical and experimental methods were developed and benchmarked against published data. Good agreement was found for the methodology of evaluation of the change of electrical properties during bending over a smooth circular surface and a non-smooth circular surface. The impact of the line-like deformations was evaluated.

If we compare the degradation of critical current occurring during the bending of a coated conductor over a smooth former and a former with surface irregularity (both parallel and perpendicular), we can see two main differences (Fig. 18, Fig. 19). The deformation caused by the perpendicular surface irregularity almost doubled the degradation of critical current in comparison to the smooth surface. In contrast, the parallel surface irregularity lowered the critical current less than when the coated conductor was bent around the smooth surface. Looking at the numerical results, we can clearly see that the local compressive strain in the REBCO layer caused by the perpendicular surface irregularity significantly increased, compared to the bending of the conductor over the smooth surface and it is the cause why the critical current decreased so much. In case of the parallel surface irregularity, the cause of the lesser degradation of critical current can be harder to see from the numerical results. However, Figure 14. gives good explanation why it is so. When the coated conductor bends around the parallel surface irregularity, it bends at a bigger bending radius, meaning the strain is lower. The current in the superconductor flows parallel to the conductor length, which means that the local strain caused by the bending of the conductor around the parallel surface irregularity hinders the flows of the current less. In case of the perpendicular surface irregularity, it creates much larger obstacle, thus significantly lowering the current.

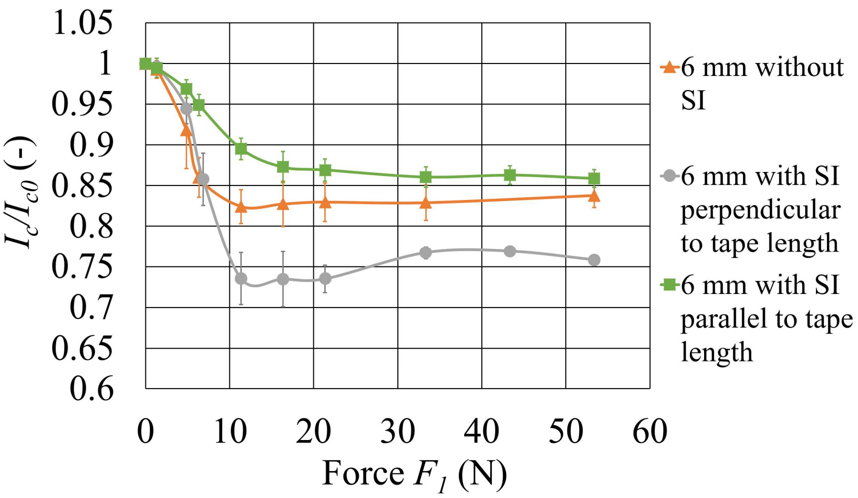


Figure 18. Measurement of the critical current degradation of the coated conductor SCS3050 bent around a smooth and a non-smooth 6 mm circular former at different bending forces [6].

In a CORT cable, the degradation of the critical current of the SuperPower coated conductors could be negligible, due to the insensitivity of the critical current of the conductors to a mechanical loading at 45° angle. However, the global and local strain, caused by the bending and the edges of the conductors, is still present. The compressive strain can limit the bending radius of the CORC/T cables, or during operation of a device, it can cause the propagation of microcracks and cable damage. If we take advantage of the findings of this study, the coated conductors could be placed in each layer with the same direction. Then the cable could be more resistant to fatigue and could possibly bend to smaller diameters without a significant degradation of critical current. However, we have to consider also that conductors laid in the layers with the same orientation are less fixed by the subsequent layers and other electrical and magnetic properties could be worse.

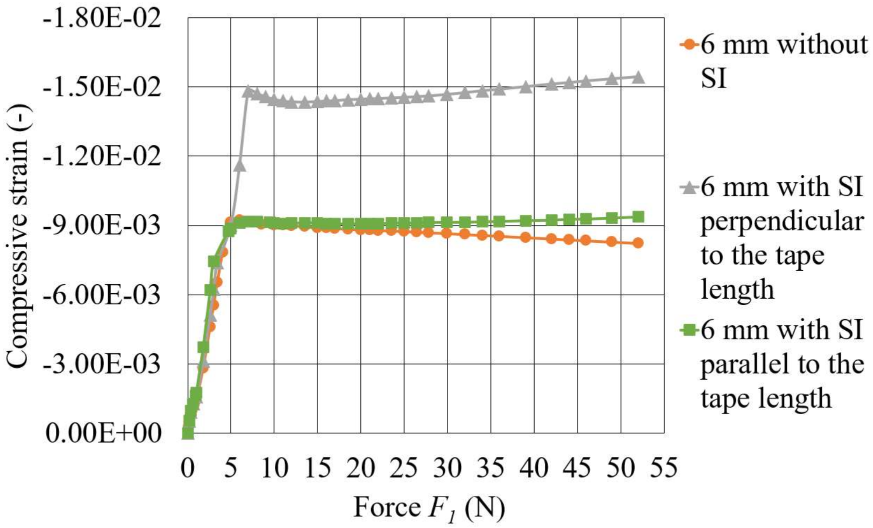


Figure 19. Numerical calculations of the maximum compressive strain caused by the bending of the coated conductor SCS3050 around a smooth and a non-smooth 6 mm circular former at different bending forces [6]

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