Narrow Strand YBCO Roebel Cable for Lowered AC Loss

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***Abstract* - We have constructed test lengths of Roebel cable from wide strips of second generation YBCO wire. The strand width is 2mm to allow for lowered AC losses in comparison with standard HTS wires. Up to 10 strands can be cut from the 40mm wide strip and assembled into a 10 strand cable with a transposition length of 90mm. Electrical measurements show good retention of critical current through the cutting and cabling processes. Initial AC loss measurements confirm the reduction expected from full width wire. Results from mechanical modeling are presented which have been used to optimise strand geometry to reduce stress concentrations. Manufacturing capability to produce up to 100m lengths has been demonstrated**.

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I. INTRODUCTION

Recent progress on development of second generation (2G) high temperature superconductor (HTS) wire based on YBCO coated conductor technology is extremely encouraging, with high-performance long lengths becoming commercially available. Progress has been also made in increasing the critical current density in moderate magnetic fields and making thicker films to increase current rating. The future for DC applications of YBCO wire such as magnets looks extremely promising.

In contrast, reducing AC losses in high-current YBCO conductors still present formidable challenges. Much work has concentrated on creating striated conductors with narrow filaments to reduce the hysteretic loss [1]. This approach however, creates two problems which are very difficult to overcome in a practical tape-shaped coated conductor. The first is how to create the twisted architecture which is necessary to preserve the gains obtained by the striation. The second is how to add or retain metallic stabiliser on the YBCO surface without reconnecting the filaments with low resistance paths.

A more practical approach to a high-current low-loss AC conductor, although a less ambitious one, is to create an YBCO Roebel cable. A Roebel cable of BSCCO conductors was developed by Siemens [2] who subsequently disclosed an approach to forming an YBCO Roebel cable [3]. The key difference with YBCO is that the conductor must be cut to shape before winding. This has subsequently been demonstrated by W. Goldacker et al [4, 5]. In this paper we report the development of automated machines to manufacture YBCO Roebel cable and report initial electrical results. We show how a Roebel cable with 2mm wide strands can be manufactured from 40mm wide YBCO strip as supplied by American Superconductor

(Westborough, MA). Cutting the Roebel strands from the widest possible tape has the advantage of increasing the utilisation of feedstock as there are unavoidable losses of material arising from cutting the Roebel shape. The 2 mm strand width allows for a nominal 50% reduction in AC losses in comparison with using standard 4-mm-wide tape in an application.

II. EXPERIMENTAL

The method chosen to manufacture the strands is mechanical punching. Due to the high cost of the feed material it is important to use a cutting method which is industrially proven and can be implemented with a high assurance of stability. We experimented with some other approaches, particularly laser cutting, but to date we have not found a laser system or other cutting method which can cut through copper-stabilised material with sufficient speed and with sufficient retained current capacity.

In Figure 1(a) we show our punching machine which punches ten strands simultaneously from the 40mm Cu-stabilised YBCO strip. The tape is accurately positioned for each stroke by a servo feeder. We have taken great care to reduce the possibility of accumulated errors in tape positioning, which could make winding long-length cables problematic as strand geometry must be synchronised over the whole length of a cable. In contrast to normal punching manufacture it is the remaining un-punched material which forms the product. The ten strands, shown in Figure 1(b), are taken up on individual tension-controlled spools. Before punching, the 40 mm wide insert strip consisting of the stack of Ni-5%W alloy substrate, buffer, HTS layer and silver passivation layer is stabilised by electroplating with 25-50 microns of copper. This coating can be single or double sided. The results reported in this paper are from material with a double-sided coating of 25 microns on each side.

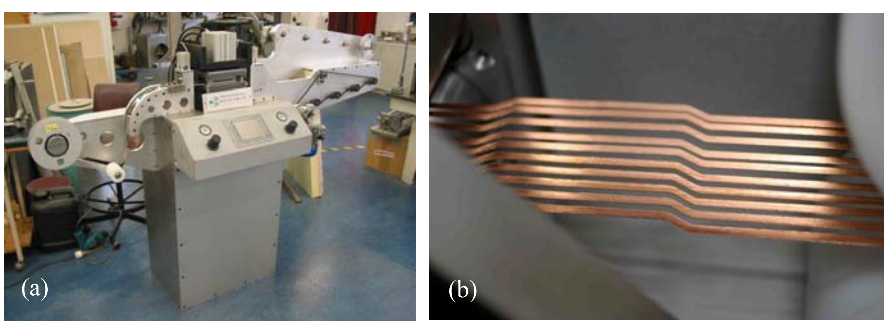

Fig. 1. (a) Automated punching machine for simultaneous cutting of 10 x 2mm strands. (b) Out feed of machine showing cut strands.

Two micrographs showing the quality of the cutting are displayed in Figure 2. The cut face is shown in Figure 2(a); there is minimal rollover of the top edge. A smearing of the top copper layer and thin Ag layer is observed. The second micrograph (b) shows the cut edge in profile. The damaged region extends only about 50 microns into the edge of the strand. The small gap seen may be an artefact of the SEM preparation it is not necessarily caused by the cutting process.

We do not have available at present a ready means to measure the I_c of wide YBCO wire at either gross or fine resolution. Therefore, a comparison of I_c per cm-width before and after cutting is not yet possible. We are developing a magnetic scanning technique as a quality control tool to address this issue. As a simple test of the I_c retention we have made single punches on a section of tape which produces the pattern of Figure 3. We measure transport I_c in samples cut from this pattern in four areas labelled A-D. The I_c results from such a sampling are shown in Figure 3.

In general the I_c in the crossover regions A and D are lower than in the straight sections. This is because the crossover region has a width of about 1.8mm rather than the 2mm of the straight sections. This reduction in width was chosen to accommodate fitting the ten strands across the width without creating added risk in the engineering of the cutting tool. In the future we believe we can overcome this limitation. The reduction in width accounts for essentially all of the reduction in I_c between the A&D and B&C sections if the best I_c results are considered. The edges of the tape (strands labelled 0,1, and 9) tend to have lower I_c than the centre region. This may be a result of our cutting process or it may be the edge regions of the supplied tape have lower I_c. There are two areas of poor I_c's, 9.0A and 12.3A, which we attribute to localised defects as they are not systematically present when the punching is repeated. The best I_c from these samples corresponds to I_c = 233A cm^{-1} which is comparable with the expectations of the strip supplier for this particular material.

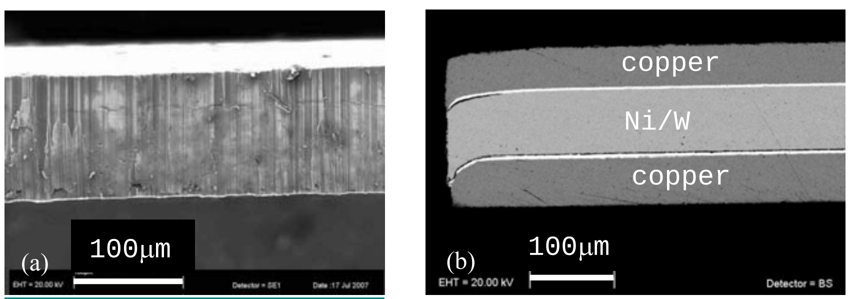

Fig. 2. (a) Punched face of YBCO strand; (b) Punched edge is to the left

The cable strands may then be insulated individually before being wound into a cable. We have developed a roll-coating system using UV cured insulation which can handle the serpentine strands without damage and without heating the strands above 100°C. The cable is wound using a planetary winding apparatus (not shown). A length of wound cable is shown in Figure 4. The cable has a total width of 5mm as there is a 1mm center gap allowed between strands. The angle of the crossover section is 30°. We have cut and wound cable up to 30m in length using the superconductor material and have cut and wound dummy cable using brass of up to 100m lengths.

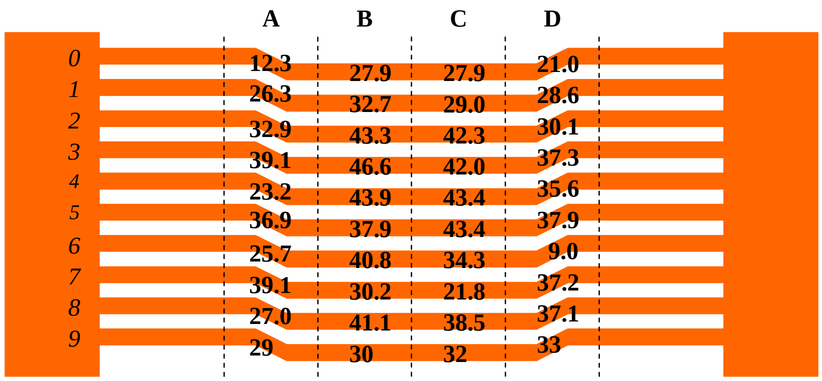

Fig. 3. I_c results from a single transposition length punched from 40mm wide feedstock. All values are in amperes.

III. MECHANICAL MODELING

We modelled the effect of strain on a cable strand to understand the influence of the Roebel shape in concentrating strain during the cable assembly process and in application environments. The numerical analysis runs were performed using the ANSYS finite element modelling package. A uniaxial tensile test in the long tape direction (*x*-direction) was simulated by applying a uniform displacement at one end of the cable such that d_x/L_x = 400x10^{-6} where d_x was the applied displacement and L_x was the length in the *x*-direction of the model. For single strand modelling, one-half of a transposition was modelled and symmetric/periodic boundary conditions were applied as appropriate. Convergence tests were performed to ensure that sufficient FE mesh resolutions were used.

Fig. 4. A finished length of YBCO Roebel cable

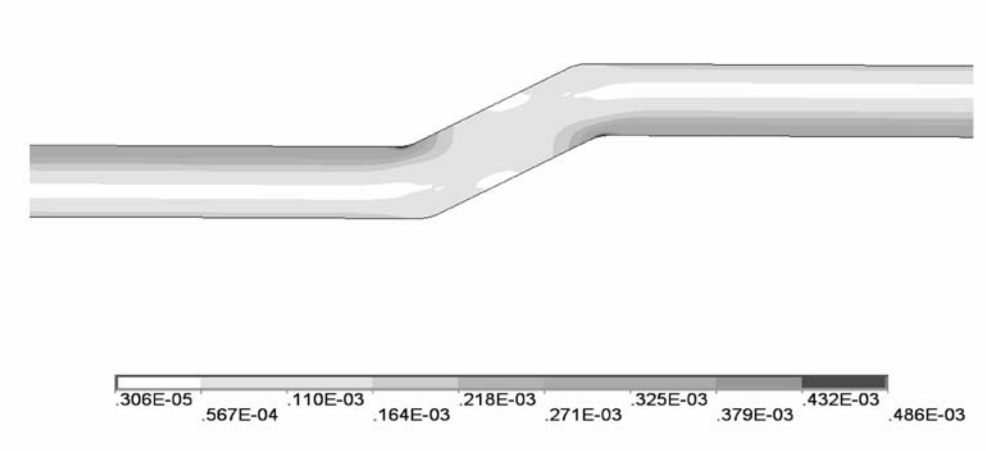

Fig. 5. von Mises strain distribution in the crossover region for a total linear displacement of 400 micro-strain.

The deformation of a single Roebel strand under a uniform applied displacement in the longitudinal direction is bending-dominated and for the cases studied the peak strain always occurred in the region of the inner fillet radius at the beginning of the crossover section. This is shown in Figure 5. The results have shown that the peak strain is significantly influenced by the size of the fillet radius (strain decreases as the inner fillet radius increases in the 3-6 mm range studied) and also the strand width (wider strands support significantly higher loads for a given strain level). The results have also shown that the peak strain is relatively insensitive to the Roebel angle and the width of the crossover region. This study is continuing with an extension to modelling multistrand configurations.

IV. ELECTRICAL RESULTS

A. Transport currents

The direct-current *E-I* curve for a cable is shown in Figure 6. The cable was formed from ten strands chosen from the center of the strip only, *i.e.*; strands labelled 4-6 in Figure 3. This cable has a critical current of approximately 400A and an *n*-value, n=23, where n is the power law exponent in fitting the *E-I* curve. The current contacts were made from copper tabs soldered to each strand and to each other. The strands in the cable were not insulated and current sharing was possible via the copper stabiliser through strand-to-strand contact. Assuming some variation in strand critical currents and current lead contact resistances, the *E-I* characteristic for a multistrand cable is not unique but will depend on where the voltage contacts are placed [6]. Hence, this result should be regarded as indicative rather than a definitive measurement.

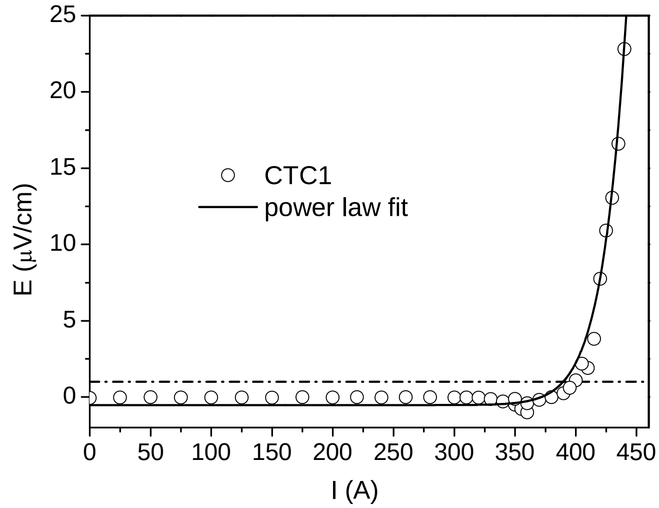

Fig. 6. *E-I* curve for Roebel cable CTC1.

B. AC loss

Magnetic AC loss measurements were made using the calibration-free method developed at Inst. of Electrical Engineering in Bratislava [7]. The measurement frequency was 59 Hz and temperature 77 K. Results for sample CTC2 are shown in Fig 7(a). This is a 10-strand 90-mm-long section of cable assembled from strands with an average I_c of 8A, as determined magnetically. The use of low I_c material helped in achieving full magnetic penetration of the material. All strands were insulated with a polymer coating.

At the lowest field amplitude the loss in the cable is less than half the total loss in the individual strands. This reduction in loss occurs, because shielding by the tapes on the outside of a stack retards the flux penetration of the inner tapes in the stack [8]. In fact, at low field amplitude the AC loss in these samples is dominated by hysteretic loss in the ferromagnetic Ni-5at%W substrates [9], but both the ferromagnetic and superconductor hysteretic loss in the inner tapes is screened.

At higher field amplitudes, the tapes are fully penetrated by the flux distribution which is nearly perpendicular to the cable, and the ferromagnetic loss (from the substrate) is negligible. The loss in the cable is then equal to the total loss in the individual strands as expected.

Figure 7(b) shows the loss in a 10-strand cable (CTC3) made from tape with higher I_c, around 200 A cm^{-1}. The loss values at high field imply a cable I_c of over 400 A by comparison with the high field limit of the Brandt expression for AC loss [10]. Again all strands were individually insulated.

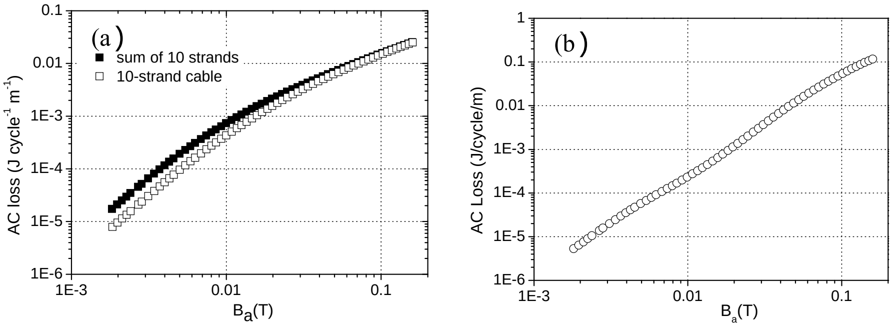

Fig. 7. AC loss for Roebel cables as a function of applied magnetic field; (a) CTC2 and (b) CTC3

V. CONCLUSIONS

We have shown it is possible to construct a Roebel cable based on 2G HTS wire with narrow strands as a means for reducing AC loss in a high-current practical conductor. Automated machines have been developed for this purpose. A strand width of 2mm is achievable using mechanical punching in a robust industrial process without loss of current capacity. We are able to manufacture ten such strands from 40-mm-wide feed tapes. Modeling of the mechanical properties of the strands has allowed us to identify the most important geometrical features for reducing strain concentration. Preliminary *E-I* measurements show the 10-strand cables have a current capacity of approximately 400A dependent on the quality of the constituent strands. AC loss measurements confirm the expected reduction in AC loss. Below the penetration field, the AC losses in the assembled cable are less than the sum of the individual strands.

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REFERENCES

[1] W.J.Carr Jr, and C.E.Oberly, *IEEE Trans. Appl. Supercond*. **9,** 1475 (1999).
[2] V.Hussennether, M.Oomen, M.Leghissa, H.–W.Neumuller, *Physica C* **401** 135 (2004).
[3] International patent application WO2003/100875
[4] W.Goldacker, A.Frank, R.Heller, S.I.Schlachter, B.Ringsdorf, K.–P.Weiss, C.Schmidt and S.Schuller, *IEEE Trans. Appl. Supercond*. **17** 3398 (2007).
[5] W.Goldacker, R.Nast, G.Kotzyba, S.I.Schlachter, A.Frank, B.Ringsdorf, C.Schmidt and P.Komarek, J. Phys.: Conf. Ser. **43** 90 (2006).
[6] F.Gömöry, L.Frolek, J.Šouc, G.Coletta and S.Spreafico, *IEEE Trans. Appl. Supercond*. **13** 1968 (2003).
[7] J Šouc, F Gömöry and M Vojenčiak, *Supercond. Sci. Technol.* **18** 592 (2005).
[8] M.P.Oomen, J.J.Rabbers, B.ten Haken, J.Rieger and M.Leghissa *Physica C* **361** 144 (2001).
[9] S.Rupp, A.D.Caplin, and M.Staines Paper 0121, EUCAS proceedings (2007), submitted.
[10] E.Brandt, and M.Indenbom, *Phys. Rev*. B **48** 12893 (1993).