Composite Superconducting MgB_2 Wires Made by Continuous Process

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Abstract—A novel manufacturing technology to produce infinitely long and cost effective composite single core MgB_2 superconductive wires has been developed [1]. The continuous process comprises unique powder feeding technology allowing micron sized Mg and nano-sized B as well as SiC dopant powders to be fed continuously to a 'U' shaped metallic sheath material (e.g. titanium, monel). Laser seam welding technology has been applied to seal the conductor seam allowing continuous wire production. Deformation characteristics of wires produced by single and bimetallic sheath materials have been studied. The $I_c(B,T)$ characteristic of the resulting products has been investigated in a dedicated helium force vapour cooling system at temperatures 20-35K and moderate external magnetic flux density up to 1 T, and also in LHe at high external magnetic flux density up to 9T. It is demonstrated that the proposed technology provides the possibility of virtually unlimited conductor lengths as well as in-line processing control, ensuring a high degree of reproducibility and consistent quality of the MgB_2 superconductor for large-scale applications. New wire feeding, sealing, reduction and forming technology enable such wires to achieve high engineering critical current density, J_e. Such generic single core MgB_2 conductors enable manufacture of multifilamentary MgB_2 conductors with desired configurations (e.g. twist pitch for transient losses and AC applications).

A. Principles of the Technology

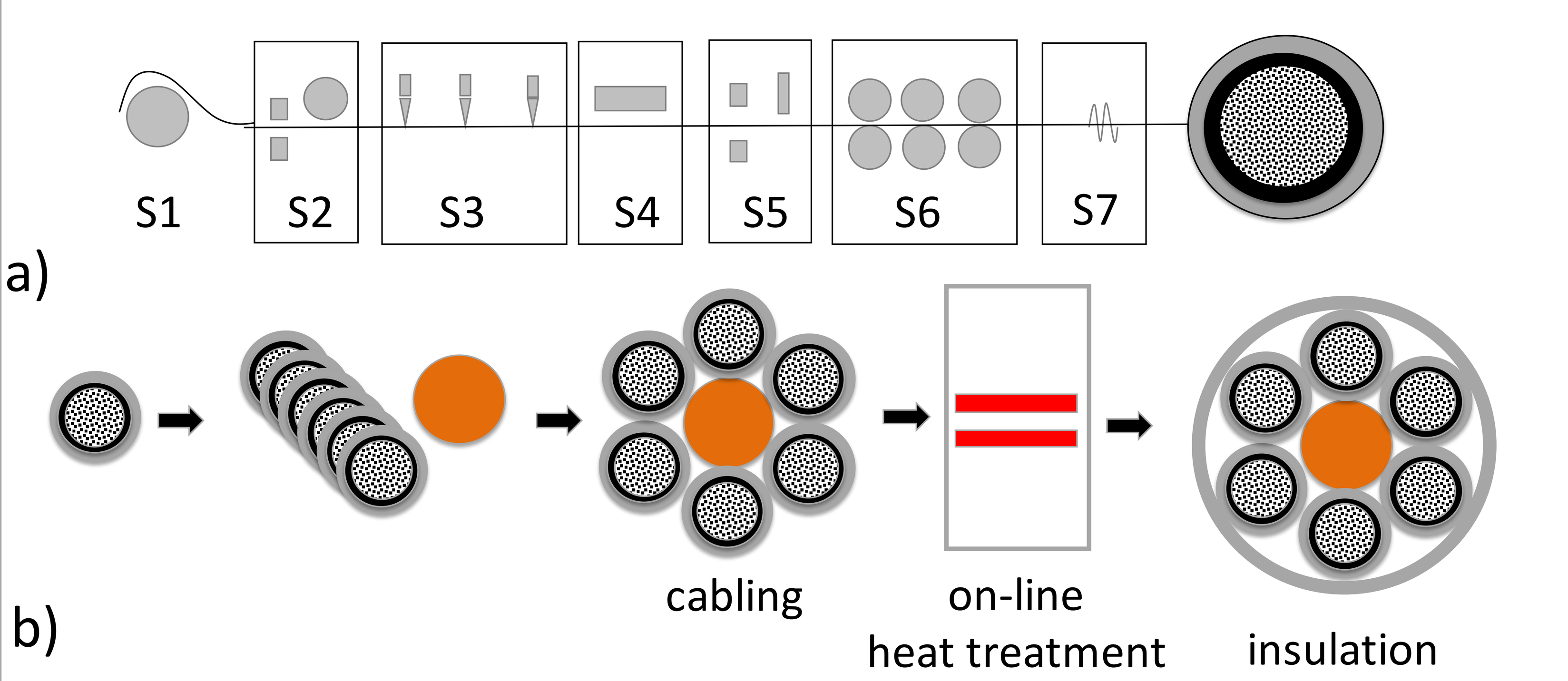

Fig. 1. Schematic illustration of the manufacturing technology stages: **a)** single core conductor: S1 - bimetallic sheath dispenser, S2 - bimetallic tape "U" profiling, S3 - nanoparticle powder delivery system into "U" profiled tape, S4 - powder thermal pre-conditioning, S5 - bimetallic tape closure and laser welding, S6 - wire reduction, S7 - eddy current control; **b)** Twisted multifilamentary MgB_2 conductor formation in protective gas atmosphere [1].

B. Powder Preparation, Feeding and Welding

In situ MgB_2 wires were prepared using amorphous boron from Pavezyum, Turkey, magnesium from Magnesium Metal Co., Turkey and SiC dopant from Iolitec, Germany. Amorphous boron has a purity of 95-97 %, magnesium has a purity of above 99.9 % with a particle size of 100-150 µm and nano SiC has a particle size of 40-60 nm. For the wires with SiC doping, doping level was fixed to 10 wt%. The mixed powders are transported into a "U" profile of e.g. monel/titanium sheath using fluidized-bed principle. The uniform fluidization is achieved with liquid carrier. During the feeding process, high level of intermixing provides further adhesion between the powders. After the nanoparticle mix filling stage, the folded "U" shaped bimetallic strip is welded using laser-seam-welding technology before further wire diameter reduction.

C. Wire Size Reduction and Twisting of Wires

The laser-welded wire is passed through a series of rollers and dies, which reduces the diameter down to 0.75 mm. Total elongation of wire from the laser-seam welding station to 0.75 mm diameter is equivalent to 98.5 % reduction in area, resulting in heavily compacted and densified wires. Six individual long length single core MgB_2 conductors (undoped or doped with SiC), together with a central copper wire, were introduced to a wire twisting machine to produce a "6+1" multifilamentary cable configuration, with twist pitches of 13 mm and 26 mm, Fig. 2

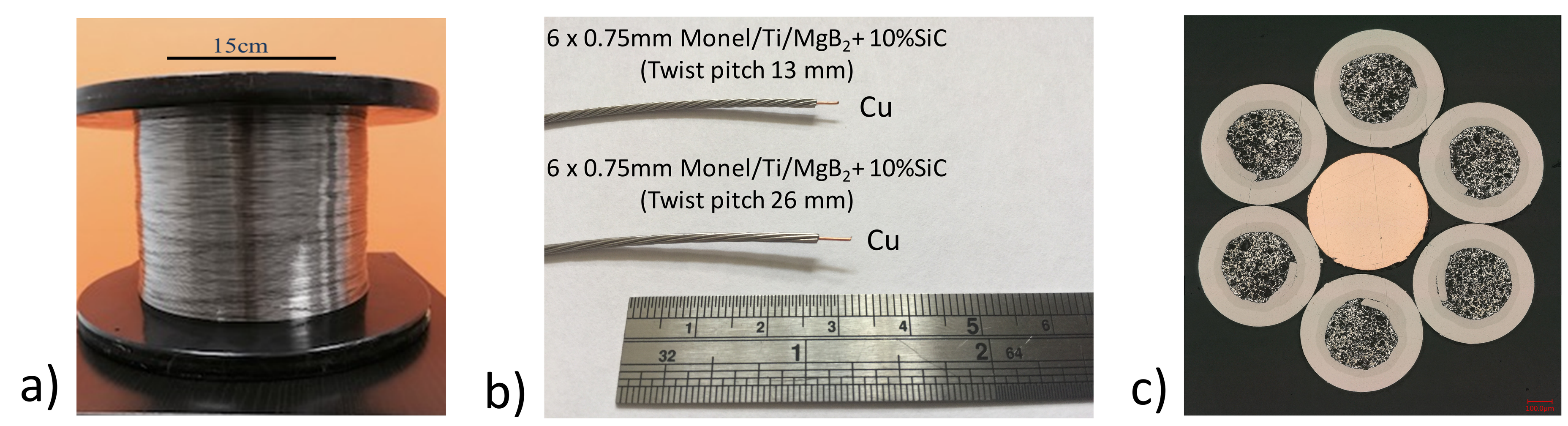

Fig. 2 a) Picture of the spool of the single core MgB_2+10wt% SiC Titanium/Monel conductor; **b)** Photograph of a "6+1" configuration cable constructed from six 0.75 mm Monel/Titanium/(MgB_2+10 wt%SiC) wires and one central copper wire showing twist pitch 13 mm and 26 mm; **c)** cross section of the "6+1" unreacted Monel/Titanium/(MgB_2+10 wt%SiC)/Cu conductor.

D. Reactive Diffusion

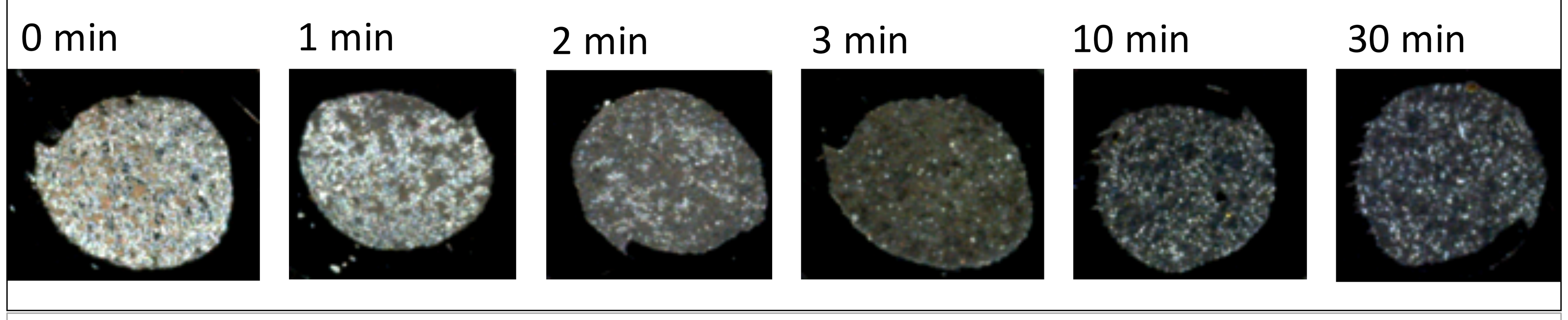

Fig. 3 Polarized reflective optical images of the MgB_2+10 wt%SiC Titanium/Monel conductor core of the wire diameter 1.27 mm, see Fig. 2 c), sintered at 700° C for different time under argon protective atmosphere: **a)** 0 min (brown areas represent boron agglomerates of amorphous boron powder, where bright areas represent Mg and SiC); **b)** 1 min, (it is evident that reaction of the Mg diffusion is very rapid); **c)** 2 min; **d)** 3 min, (after 3 minutes there is no strong evidence of the unreacted Mg zones however unreacted Mg pockets remain in the cross section); **e)** 10 min (one may notice developed difference in the reflective light spectrum in relation to samples annealed at shorter times); **f)** 30 min (reflective polarized image after 60 min sintering looks identical as for wire annealed after 30 min). (Pictures **e)** and **f)** show some amount of blue-like color, which is associated with formation of Mg_2Si), see Fig. 5.

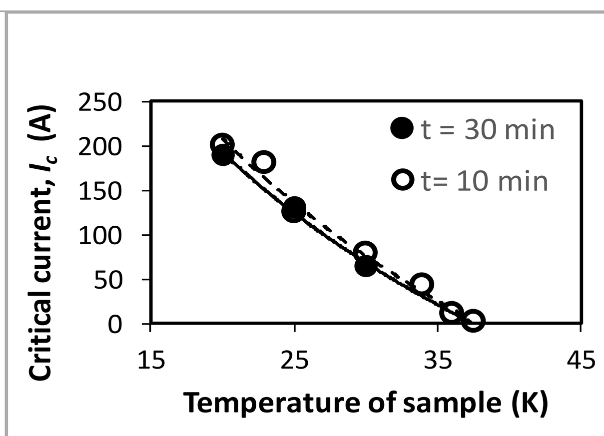

Fig. 4 Comparison of critical current values of Monel/Titanium sheathed MgB_2+10 wt%SiC 0.75 mm wires versus temperature after sintering at 700° C for 10 min and 30 min under magnetic field of 1 Tesla. It is noticeable that values for 10 min are slightly higher than for longer time.

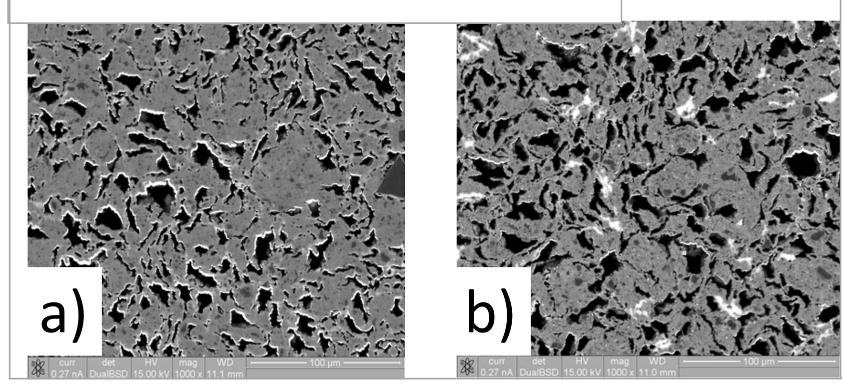

Fig. 5. SEM image of the central core of a 0.75 mm Monel/Titanium sheathed MgB_2 wires sintered at 700° C for 30 min: **a)** MgB_2, **b)** MgB_2+10 wt% SiC showing white Mg_2Si inclusions, the black areas represent porosity. The bar at the bottom of images represents 100 µm distance.

E. Helium Cooled High Magnetic Field Critical Current Measurements of Wires and Bundles

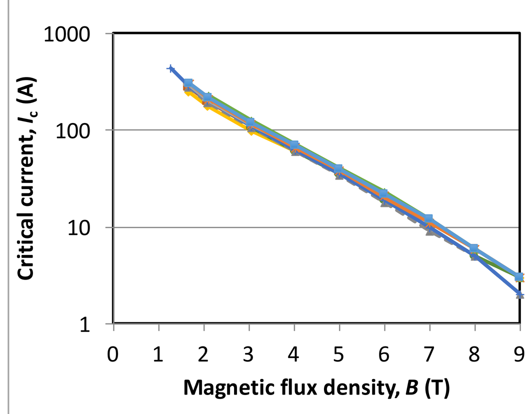

Fig. 6. Transport critical current measurements I_c of a single core doped sheathed MgB_2 conductor measured at 4.2 K over the length of 9.1 km, where the samples for measurements were extracted and measured every 0,7 km. (2 samples were extracted and measured every 0,7 km, resulting in 12 measurements, resulting in 12 overlapping curves). The diameter of the wire is 0.75mm and cross section of the superconducting core is equal to 0.1370 mm² corresponding to 31% fill factor.

Table 1 Critical current, I_c and n-values measured at 3T, 4T and 5T and at 4.2K for doped conductor, 13 mm twist pitch

Conductor sample length 2.6 m; twist pitch 13 mm, wire diameter 0.75 mm

	3T		4T		5T	
Voltage taps	I_c (A)	n (-)	I_c (A)	n (-)	I_c (A)	n (-)
V1	-	-	415	47.9	229	37.9
V2	-	-	412	49.2	228	38
V3	643	23.6	377	19.5	214	20
V4	649	19.8	386	20.8	218	21.6
V5	698	57.1	405	41.8	223	30.3
V6	697	49.2	408	43.4	229	40.6
Cabled 1 filament	111.96		66.75		37.25	
Cabled/Avg.	100%		103%		100%	
Avg. 1 filament	112.1		65		37.2	

Conclusions

- It is documented that a novel manufacturing technology to produce infinitely long and cost effective composite single core MgB_2 superconductive wires that effectively can be twisted to "6+1" conductor configuration with twist pitch 26 mm.
- The critical current density after twisting proves to be identical to the critical current density of a single core conductor.
- Development of alternative sheath materials such as mild steel and austenitic stainless steel are in progress to enable cost reduction without degradation of superconductive and mechanical properties.
- There is also work on improved cryostability of the wires in "6+1" conductor which will be reported in the near future.

[1] S. Atamert, M. N. Kutucku, J-L Scandella, A. Baskys, Z. Zhong and B. A. Glowacki, *IEEE Trans. Appl. Supercond*, vol. 26, no. 3, April 2016, 6201104