Ongoing Efforts at Internal-Tin Nb_3Sn Strand with Higher J_{cn} and Lower Hysteresis Loss

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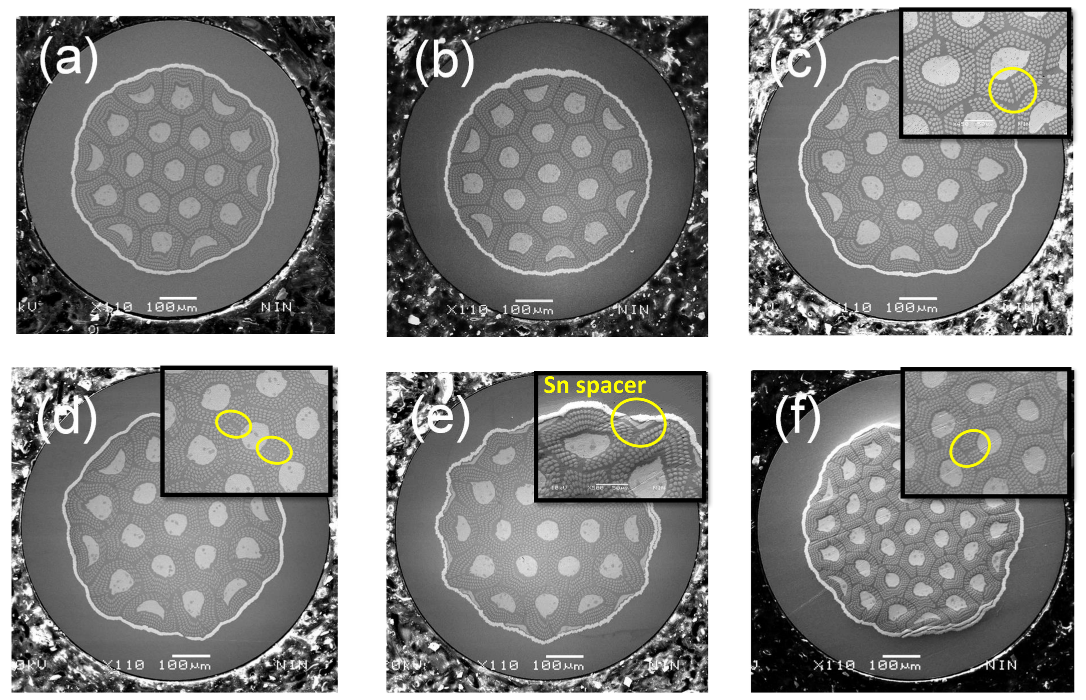
Background

For ITER Nb_3Sn strand, the first technical challenge could be the precise contradiction of high J_{cn} and low hysteresis loss. J_{cn} could be easily improved by optimization of structure, Nb/Sn/Cu ratio and heat treatment while correspondingly hysteresis loss could unexpectedly be improved. Even in mass production stage, WST has been taking great efforts to obtain higher J_{cn} and lower hysteresis loss. Better control of process and deformation are more remarkable for hysteresis loss when improving J_{cn}. This situation has been reflected by the actual performance of IT Nb_3Sn strand of WST.

Europe DEMO and CFETR proposed higher performance requirements which the ITER Nb_3Sn strand could not reach only by optimization of ITER Nb_3Sn strand. These years, based on ITER IT Nb_3Sn strand, WST has carried out plenty of research in aspect of Cu split, Sn spacer and deformation optimization.

Experiments



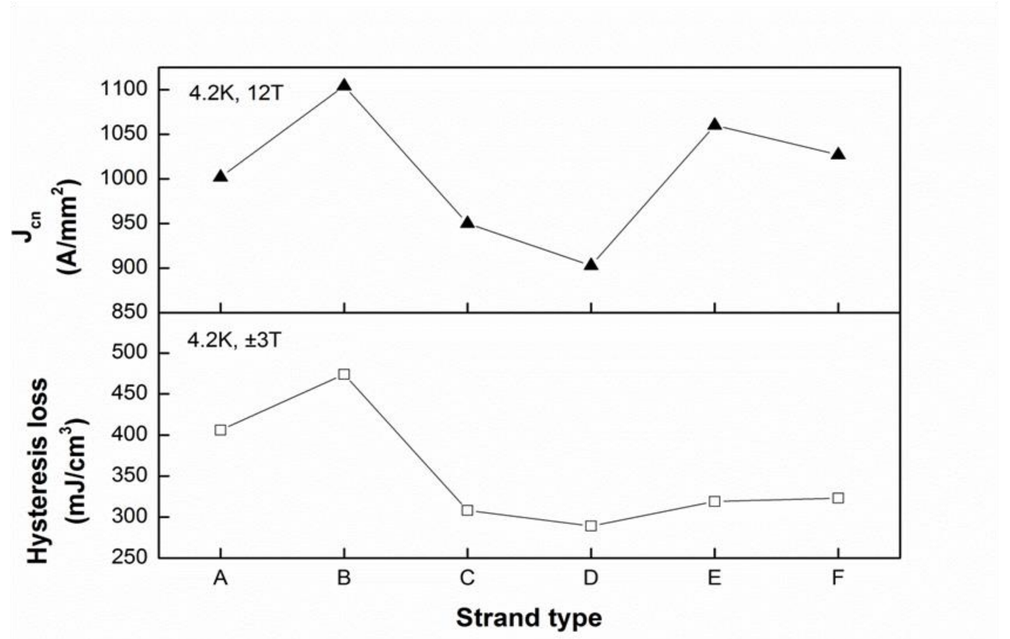
Parameters and Structure of Nb_3Sn strands

Type	A	B	C	D	E	F
Number of subelements	19	19	19	19	19	37
Number of filaments	3040	3040	2964	2888	2964	5772
Cu split	No	No	1	2	1	1
Sn spacer	No	No	No	No	Yes	No

(a) Type A: ITER Nb_3Sn strand.
(b) Type B: ITER strand after deformation optimization.
(c) Type C: One Cu split in each subelement.
(d) Type D: Two Cu splits in each subelement.
(e) Type E: One Cu split in each subelement and six Sn spacers.
(f) Type F: 37 subelements with one Cu split each.

Results

J_{cn} and hysteresis loss

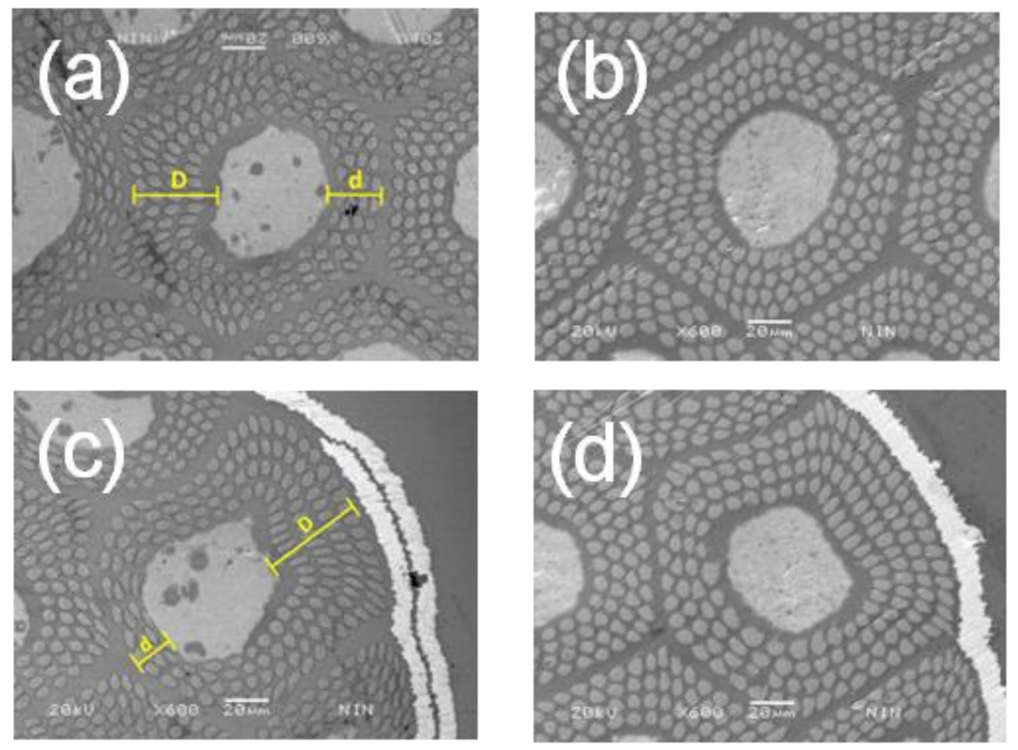


- Type A is typical ITER Nb_3Sn strand with J_{cn} of 1002 A/mm² and hysteresis loss of 406 mJ/cm³. After optimizing deformation of Type A strand, J_{cn} of type B strand is increased to 1104 A/mm², but hysteresis loss is also increased to 474 mJ/cm³.

- Type C strand with one Cu split and type D with two Cu splits show J_{cn} decrease of 5% and 10% compared with Type A. Meanwhile Nb area loss is 2.5% for type C and 5% for Type D. Surprisingly hysteresis loss is reduced to 308 mJ/cm³ for Type C and 289 mJ/cm³ for Type D, notably lower than Type A.

- J_{cn} of Type E strand reaches 1060 A/mm², 12% higher than Type C strand, but hysteresis loss almost remains the same level. For Type F, J_{cn} is 8% higher and hysteresis loss is 5% higher than Type C strand.

Effect of deformation



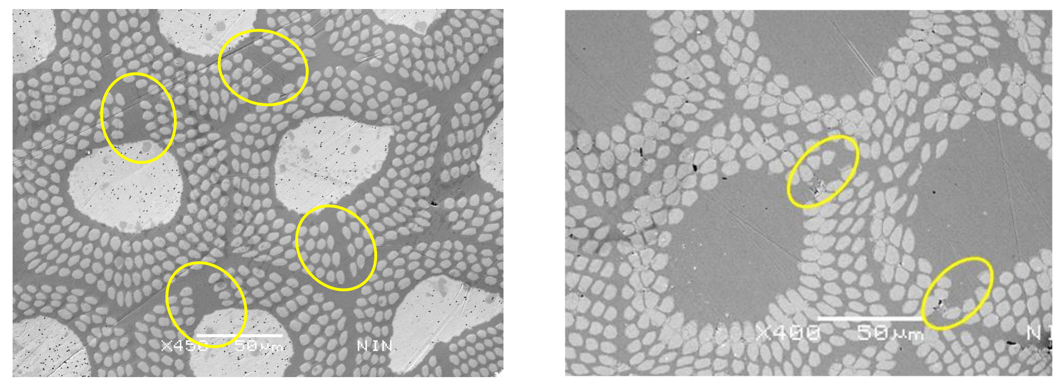
- Distortion rate D/d is defined as the thickness ratio of outer ring to inner ring, as shown in (a).

- After deformation optimization, from (a) and (b) D/d is 1.67 for Type A and 1.21 for Type B. From (c) and (d), D/d is 2.46 for Type A and 1.33 for Type B.

- After optimization subelements are more homogeneous. J_{cn} is by 10.2% improved from 1002 A/mm² to 1104 A/mm², while hysteresis loss is also by 16.7% improved from 406 mJ/cm³ to 474 mJ/cm³.

- It could be deduced that better deformation benefit to higher current density. But after heat treatment the bridged filament ring is bigger, which may induce the increase of hysteresis level.

Effect of Cu split

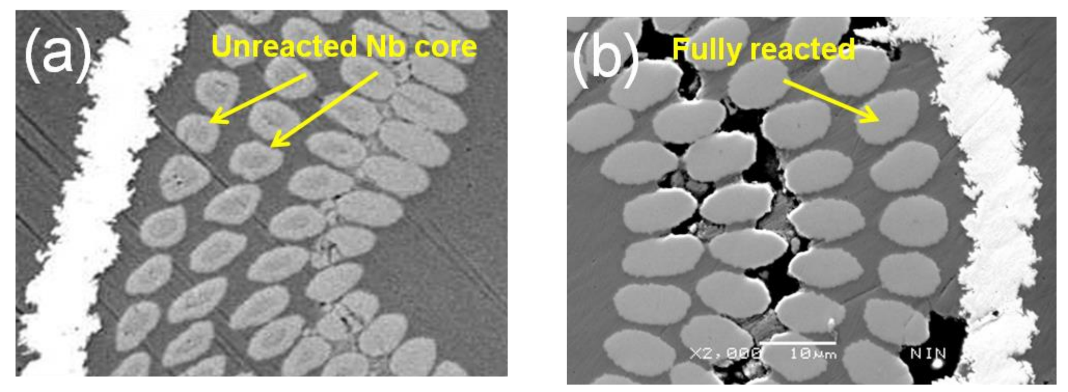


- Cu splits were used to replace a few Nb filaments in each subelement, to break the ring of bridging Nb_3Sn filaments after heat treatment, for lower hysteresis loss level.

- Hysteresis loss is dramatically reduced by the Cu splits. Hysteresis loss is reduced to 308 mJ/cm³ for Type C and 289 mJ/cm³ for Type D, which are 24% and 29% lower than Type A respectively. It is the first time for us to obtain such low hysteresis loss level.

- Nevertheless as expected J_{cn} level of Type C strand and Type D strand are both decreased at the same time. J_{cn} is reduced to 950 A/mm² for Type C and 903 A/mm² for Type D, 5% and 10% lower than Type A. Cu splits lead to the 2.5% and 5% loss of Nb area compared with Type A. Thus J_{cn} almost drops twice faster as the loss of Nb area, which could be attributed to a little Sn consumed by the Cu splits instead of reacting with Nb.

Effect of reaction degree



- The filaments are not fully reacted after heat treatment in Type C strand, as shown in (a). For Type E strand, six Sn-2wt.%Ti/Cu spacers were located between the outermost subelements and Ta barrier. All the filaments are fully reacted as shown in (b).

- J_{cn} of Type E strand is raised to 1060 A/mm² from 950 A/mm² of Type C strand. But the hysteresis loss of Type E strand nearly remains the same as type C strand.

- Type F strand was prepared by assembling 37 subelements each with one Cu split to reduce the size of subelement. After heat treatment fully reacted Nb_3Sn filaments are found across the strand. Compared with Type C strand with 19 subelements each with one Cu split, Type F strand exhibits J_{cn} of 1027A/mm² and hysteresis loss of 323 mJ/cm³, 8% and 5% higher than Type C strand, respectively.

Conclusions

- Drawing condition optimization could help better deformation of subelements and filaments, which results in the increase of J_{cn} and unexpected increase of hysteresis loss.

- Cu splits could break the bridged filament ring after heat treatment and reduce the effective filament diameter. Cu splits are most efficient to reduce the level of hysteresis loss in our research history. However, the loss of Nb area due to Cu splits results in the decrease of J_{cn}.

- Sn spacers and 37 subelements could enhance the reaction degree of the filaments in the outermost subelements. 37-subelement strand guarantees homogeneous deformation of subelements and Ta barrier.

- From above, 37-subelement strand and one Cu split in each subelement has solved the contradiction between J_{cn} and hysteresis.

- Up to now, 37-subelement strand is the most promising Nb_3Sn strand for the future fusion application.

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