PAPER • **OPEN ACCESS**

The Effect of Reinforcement Substrate Alloy Selection on Mechanical Properties of REBCO Coated Conductors

To cite this article: K. J. Radcliff *et al* 2020 *IOP Conf. Ser.: Mater. Sci. Eng.* **756** 012023

IOP Conf. Series: Materials Science and Engineering **756** (2020) 012023 doi:10.1088/1757-899X/756/1/012023

The Effect of Reinforcement Substrate Alloy Selection on Mechanical Properties of REBCO Coated Conductors

K. J. Radcliff[1], R. P. Walsh[1], D. C. Larbalestier[1] and Seungyong Hahn[1, 2]

[1]National High Magnetic Field Laboratory, 2031 E. Paul Dirac Drive, Tallahassee, FL 32310, US

[2]Department of Electrical and Computer Engineering, Seoul National University, Gwanak-ro 1, Gwanak-gu, Seoul, Korea 08826

Abstract. Rare earth Barium Copper Oxide (REBCO) coated conductors are promising candidates for high field (>25 T) user magnets. However, as the demand for higher fields increase, so does the potential to overstrain the conductors being used. Coated conductor substrates, such as 310s stainless steel and the super-alloy Hastelloy C276, serve as the backbone for mechanical strength in these conductors. Both substrate alloys share similar properties when optimally processed into strips prior to manufacturing of the REBCO coated conductor. We find that with subsequent REBCO manufacturing processes the strength of the substrate changes, the magnitude of which depends on whether Hastelloy C276 or 310s stainless steel is used. In this study, we investigate the stress-strain variability found in coated conductors and how the manufacturing process affects the mechanical properties. The manufacturing step of concern is the short time that the substrate is exposed to high temperature (700 to 800 C) during the REBCO deposition process. To better relate manufacturing processes and mechanical properties, we subjected bare substrates to different heat treatments at 700, 750, and 800 C for 15 minutes each. With post heat-treatment room-temperature tensile tests, we found that the 310s stainless steel substrate was sensitive to the variations of time and temperature, exhibiting yield strength reductions of 20 to 50 % depending on the heat treatment. By contrast, Hastelloy C276 did not weaken and initially showed strengthening effects with exposure to the lower temperature heat treatments. Coated conductor manufactures may prefer 310s stainless steel as their substrate due to cost and availability, however, moving to Hastelloy C276 will offer better mechanical robustness and reproducibility of mechanical properties within their coated conductor.

1. Introduction

REBCO coated conductors are increasingly becoming more popular for next generation high field magnets. With their high current density and relatively high operating temperature allowing a wide range of magnet applications. However, these tape conductors are quite sensitive to the effects of strain during manufacturing and in use operations. Mechanical properties of REBCO coated conductors show variable strength depending on the type of substrate used to reinforce the conductor. Evidence shows this variability could come from the vapour deposition process during manufacturing of the coated conductor. The two types of commonly used substrates are Hastelloy C276 and 310s stainless steel are used to perform this systematic study on the effects of deposition temperature during the manufacturing process.

2. Material Properties

310s stainless steel is a high nickel austenitic steel alloy that allows increased resistance to strain induced martensitic transformations. Hastelloy C276 is a nickel- tungsten superalloy with high strength and non-magnetic properties [1]. Both alloys are used in high temperature applications for their strength allowing them to be strong candidates to handle annealing temperatures during the vapour deposition process. Table 1 shows the chemical composition of both 310s stainless steel and Hastelloy C276.

Table 1: Chemical composition in wt % of 310s stainless steel and Hastelloy C276.

	Ni	Mo	Cr	Fe	W	Mn	Co	C	V	P	S	Si
Hastelloy C276	Balance	15-17	14.5-16.5	4.0-7.0	3-4.5	1.0	2.5	0.01	0.35	0.4	0.03	0.08
310s Stainless Steel	19-22	-	24-26	Balance	-	2.0	-	0.25	-	0.045	0.030	1.50

The 310s stainless steel samples were 100 µm thick and four mm. The Hastelloy samples were 30 and 50 µm thick and 12 mm wide.

3. Procedure

Four different conditions of both substrates were tested. Two samples for each substrate were tested in the as received condition, after 700 °C, 750 °C, and 800 °C heat treatment. To simulate the temperature excursions during the vapour deposition process, three heat treatment conditions were done on 100 µm 310s stainless steel and on 50 and 30 µm Hastelloy C276. Figure 1 shows the temperature profiles for each heat treatment; each heat treatment took about three hours to reach desired temperature was held at temperature for a total of 15 minutes inside an argon environment and then was air cooled. The temperatures were chosen due to a previous report on IBAD temperature during YBCO manufacturing being approximately 750 °C [2].

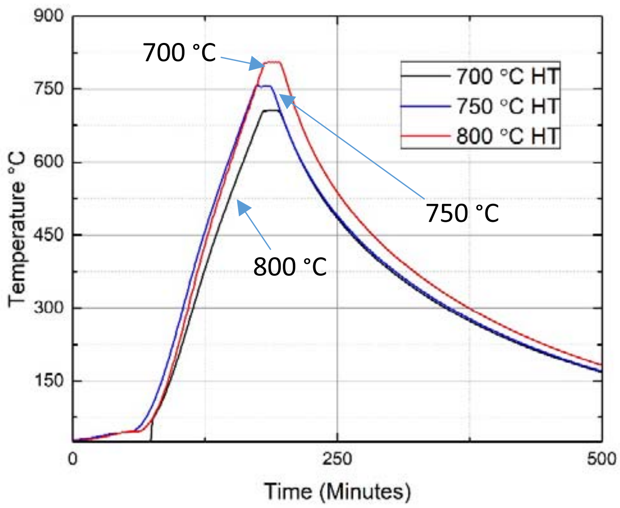

Figure 1: The annealing temperature profiles on bare 310s stainless steel and Hastelloy C276 substrates [9].

Room temperature tensile test are performed according to the ASTM E8 standard [2]. Tests are conducted in displacement control at a rate = 0.5 mm/min (for an elastic strain rate = $1.67*10^{-4}$ Ɛ s^{-1}) using a clip-on extensometer. An unload cycle is performed during the tensile test at 0.15% strain for modulus determination and strain is measured with a 50 mm gage length clip-on extensometer.

4. Results and Discussion

The tensile test results are shown in Table 2. The initial results of the as received condition of the Hastelloy C276 and 310s stainless steel seen in figure 2(A) shows that each substrate starts in the cold-worked condition. The 310s stainless steel has a yield strength of about 1237 MPa which corresponds to about 40 % cold worked [5] while the as-received yield strength of Hastelloy C276 is approximately 1464 MPa, independent of Hastelloy C276 thickness. Figures 2(A) – (D) show the effect of heat-treatment temperature on the stress-strain relationship of the Hastelloy C276 and 310s stainless steel substrates. Intuition suggest that relatively no change should occur to the substrates at after the 700 °C heat treatment since both materials are used for high temperature applications. Figure 2(B) suggest that is not

IOP Conf. Series: Materials Science and Engineering **756** (2020) 012023 doi:10.1088/1757-899X/756/1/012023

necessarily the case for the 310s stainless steel. The yield strength of the 310s stainless steel dropped 22 percent to 965 MPa from the as-received condition.

Table 2: Tensile test results of bare 310s stainless steel and Hastelloy C276 substrates tested at 293 K

Material	Condition	Test Temp	Young's Modulus	0.2 % Yield Strength
		K	GPa	MPa
310s Stainless Steel	AR	293	174	1237
	700 °C	293	163	965
	750 °C	293	164	619
	800 °C	293	179	527

Material	Condition	Test Temp	Young's Modulus	0.2 % Yield Strength
		K	GPa	MPa
Hastelloy C276	AR	293	181	1464
	700 °C	293	209	1524
	750 °C	293	209	1477
	800 °C	293	202	1224

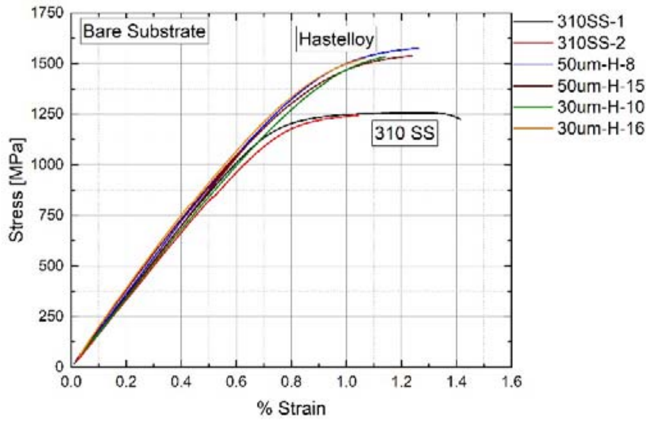

Figure 2(A) : As received stress-strain relationship of Bare Hastelloy C276 and 310s stainless steel at 293 K [9].

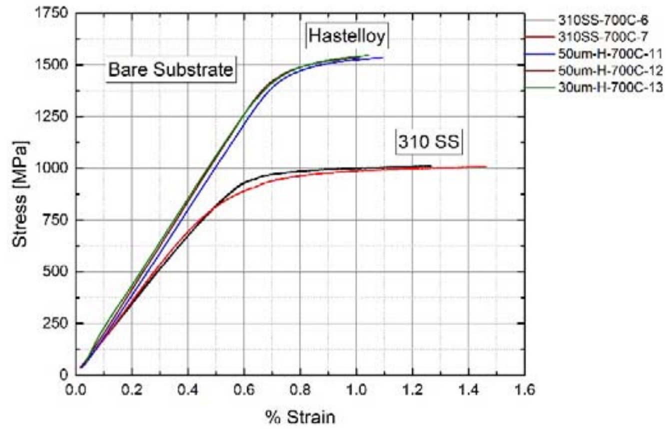

Figure 2(B): 700 C heat treatment effect on stress-strain relationship of Bare Hastelloy C276 and 310s stainless steel at 293 K [9].

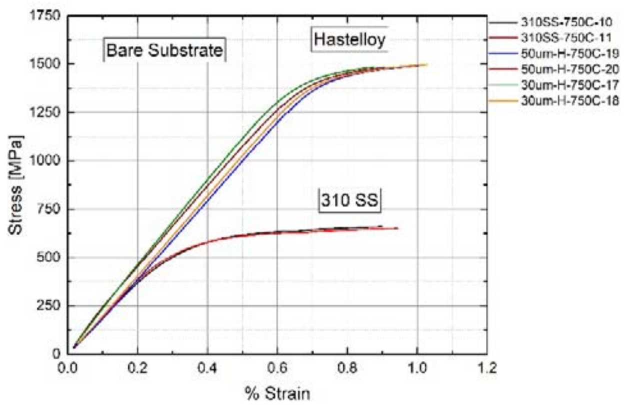

Figure 2(C): 750 C heat treatment effect on stress-strain relationship of Bare Hastelloy C276 and 310s stainless steel at 293 K [9].

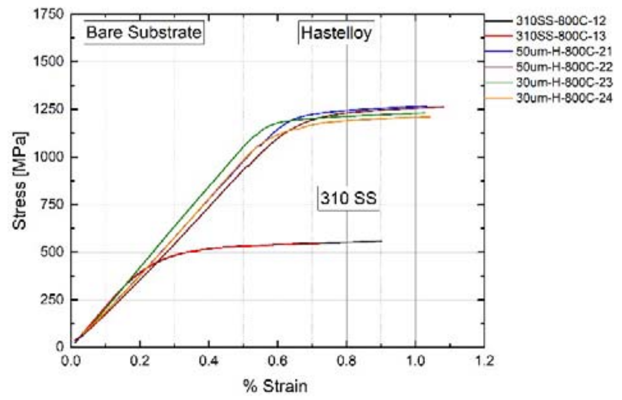

Figure 2(D): 800 C heat treatment effect on stress-strain relationship of Bare Hastelloy C276 and 310s stainless steel at 293 K [9].

The mechanical properties of Hastelloy C276 after the 750 °C heat treatment showed no apparent difference when compared to the 700 C heat treatment. The 310s stainless steel however, showed another distinct drop in yield strength. The yield strength of the 310s stainless steel dropped to 619 MPa, about half the strength of the as-received condition. Figure 2(D) shows the effects of heating the substrates at 800 °C. Surprisingly, Hastelloy C276 was affected by this annealing temperature causing a 240 MPa drop in yield from the as received condition. 310s stainless steel yield strength dropped to 510 MPa. One potential reason the Hastelloy C276 experience some weakening is possibly due to the 800 °C heat treatment is close the maximum precipitation temperature of 871 C [5]. Slight variation can also be seen in figure 2 (C-D) for Hastelloy C276 yield strength but with similar elastic modulus. This scatter in data has been previously reported in Clickner et. al [5] between batches of Hastelloy C276 substrate.

Figure 3 shown below, gives an average trend of the samples tested in each of the four conditions. It is immediately apparent that the 310s stainless steel is unmistakably affected by temperature excursions during the REBCO manufacturing process. Hastelloy C276 on the other hand is weakly effected by these temperatures in terms of yield strength. Interestingly, Hastelloy C276 had a strengthening effect on the elastic modulus from the 700 and 750 °C heat treatment. It can also been seen that the 800 °C annealing on the 310s stainless steel gave it a slight curvature to the modulus. Barth et. al. [7] showed a similar rounding or curvature effect in REBCO coated conductors that utilized 310s stainless steel conductors.

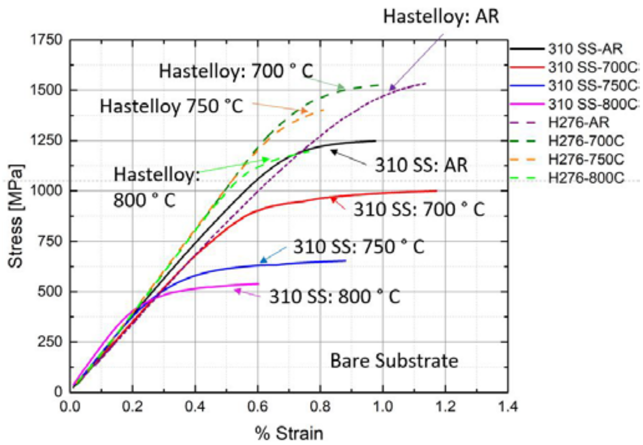

Figure 3: Average stress-strain trend of as received and heat treated 310s stainless steel and Hastelloy C276 bare substrate tested at 293 K [9].

The yield strength vs heat-treat temperature can be seen in figure 4 for both substrates. The trend of strengthening of the Hastelloy C276 and weakening of the 310s stainless steel becomes more apparent. When the 310s stainless steel is compared to the Hastelloy C276, the difference of yield strength is striking. Over the range of temperatures, Hastelloy C276 outcompetes with the 310s stainless steel. The trend of which the 310s stainless steel weakens is similar to previously reported effects in the ASM handbook of stainless steels [5] and in Shi. L et al [8].

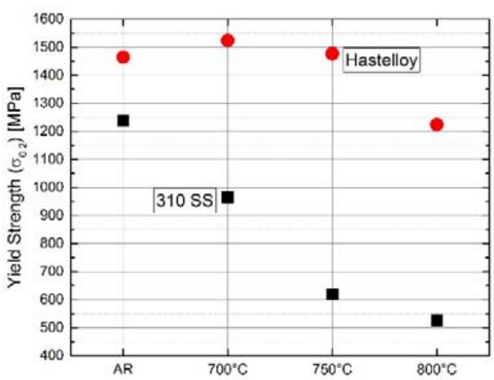

Figure 4: Yield strength vs heat treatment on 310s stainless steel (black square) and Hastelloy C276 (red circle) [9].

5. Conclusion

Simulating the temperatures that could be seen during the manufacturing of REBCO coated conductors shows how two common types of substrates are affected. 310s stainless steel being a high nickel and chromium alloy is no match in terms of retaining strength to Hastelloy C276. Hastelloy C276 suffered no drastic weakening effect, even though after the 800 °C heat treatment it was approximately the same yield strength of the 310s stainless steel in its initial cold-worked state. Substrates used for REBCO coated conductors should display no changes in mechanical properties after manufacturing to ensure strain tolerance of the coated conductor is ideal [10].

6. References

[1] T. Nagaishi, Y. Shingai, M. Konishi, T. Taneda, H. Ota, G. Honda, T. Kato, K. Ohmatsu, Development of REBCO coated conductors on textured metallic substrates, Physica C: Superconductivity, Volume 469, Issues 15–20, 2009, Pages 1311-1315,

[2] S. Gnanarajan and N. Savvides,\Dual ion beam assisted magnetron deposition of biaxially textured ysz and ybco/ysz thin _lms," Surface and Coatings Technology, vol. 305, pp. 116 { 122, 2016.

[3] ASTM International. *E8/E8M-16a Standard Test Methods for Tension Testing of Metallic Materials*. West Conshohocken, PA, 2016. Web. 17 Jul 2019. <https://doi.org/10.1520/E0008_E0008M-16A>

[4] J. R. Davis, “Low-Temperature Properties.” ASM Specialty Handbook: Stainless Steels, 1994, pp. 495-504

[5] R. B. Leonard, \Thermal stability of hastelloy alloy c-276," CORROSION, vol. 25, no. 5, pp. 222{232, 1969. [Online]. Available: https://doi.org/10.5006/0010-9312-25.5.222

[6] C.C. Clickner, J.W. Ekin, N. Cheggour, C.L.H. Thieme, Y. Qiao, Y.-Y. Xie, A. Goyal, Mechanical properties of pure Ni and Ni-alloy substrate materials for Y–Ba–Cu–O coated superconductors, Cryogenics, Volume 46, Issue 6, 2006, Pages 432-438.

[7] Barth, C., Mondonico, G., and Senatore, C., Electro-mechanical properties of REBCO coated conductors from various industrial manufacturers at 77 K, self-field and 4.2, 19 T, IOP publishing, Volume 28.

[8] L. Shi, D.O. Northwood, The mechanical behaviour of an AISI type 310 stainless steel,Acta Metallurgica et Materialia, Volume 43, Issue 2, 1995, pp. 453-460,

[9] K. Radcliff, 2017, Mechanical Properties of SuperPower and SuNAM REBCO Coated Conductor, Master Thesis, Florida State University, Tallahassee.

[10] R. P. Walsh, D. McRae, W. D. Markiewicz, J. Lu and V. J. Toplosky, "The 77-K Stress and Strain Dependence of the Critical Current of YBCO Coated Conductors and Lap Joints," in *IEEE Transactions on Applied Superconductivity*, vol. 22, no. 1, pp. 8400406-8400406, Feb. 2012, Art no. 8400406.

Acknowledgments

This work was supported by the National High Magnetic Field Laboratory (which is supported by the National Science Foundation under NSF/DMR-1157490/1664779), the State of Florida. A part of work by S. Hahn was supported by the National Research Foundation of Korea as a part of Mid-Career Research Program (No. 2018R1A2B3009249).