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Mechanical properties of pure Ni and Ni-alloy substrate materials for Y–Ba–Cu–O coated superconductors ☆

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Abstract

Mechanical properties of rolling-assisted, biaxially-textured substrates (RABiTS) and substrates for ion-beam assisted deposition (IBAD) coated superconductors are measured at room temperature, 76, and 4 K. Yield strength, Young's modulus, and the proportional limit of elasticity are determined, tabulated and compared. Results obtained are intended to serve as a database of mechanical properties of substrates having the same anneal state and texture as those incorporated in the general class of RE–Ba–Cu–O coated conductor composites (RE = rare earth). The RABiTS materials measured are pure Ni, Ni–13at.%Cr, Ni–3at.%W–2at.%Fe, Ni–10at.%Cr–2at.%W, and Ni–5at.%W. The IBAD substrate materials included Inconel 625 and Hastelloy C-276. The Ni alloys are substantially stronger and show higher strains at the proportional limit than those of pure Ni. Substrates fully coated with buffer layers, ≈1 μm of Y–Ba–Cu–O, and 3–5 μm of Ag have similar mechanical properties (at 76 K) as the substrate alone. Somewhat surprisingly, plating an additional 30–40 μm of Cu stabilizer onto high-yield-strength (690 MPa) Hastelloy coated conductors ∼100 μm thick, reduces the overall yield strength of the composite structure by only about 10–12% at 76 K and 12–14% at room temperature; this indicates that the Cu layer, despite its relatively soft nature, contributes significantly to the overall strength of even high-strength coated conductors.

Keywords: Composite conductors (A); High-T_c superconductors (A); Mechanical properties (C); Superconducting cables (A)

1. Introduction

Coated superconductors are being considered for a number of commercial applications, including power transmission lines, windings of high-field magnets, ship propulsion motors, and other applications where high-temperature superconductors offer smaller, lighter packaging, quieter operation and lower power consumption than present equipment. Selection of suitable substrate materials for coated conductors is critical for both conductor fabrication and performance. The tolerance of the critical-current density of these composites to stress and strain was found to be highly dependent on the mechanical properties of the substrate material [1–4]. This article presents a database of the mechanical properties of substrate materials being considered for YBCO coated conductors.

The mechanical properties of particular interest are the Young's modulus, yield strength, and the strain at the proportional limit of elasticity (elastic-strain limit). Since these conductors will be subjected to mechanical stresses in handling at room temperature, as well as in low temper-

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ature service, these mechanical properties are measured at 295, 76, and 4 K.

Stress–strain characteristics were measured for rolling-assisted, biaxially-textured substrate tapes (RABiTS) [5] made of pure Ni, Ni–13at.%Cr, Ni–3at.%W–2at.%Fe, Ni–10at.%Cr–2at.%W and Ni–5at.%W [6,7]. Substrates for ion-beam assisted deposition (IBAD) coated conductors [8–10], Inconel 625, and Hastelloy C-276, were also measured and the results tabulated. In addition, fully coated Hastelloy C-276 and Ni–5at.%W substrates with buffer layer, YBCO, and Ag/Cu coatings are compared to bare substrates to verify that the mechanical properties of the substrate material dominate the mechanical properties of the fully coated conductor.

2. Experimental methods

The apparatus for measuring stress–strain characteristics was constructed to investigate very soft, thin (tens of micrometers thick) substrates at room and cryogenic temperatures. We considered various experimental techniques to measure strain. Use of conventional strain gages was not practical since the gage, and adhesives for binding it to the sample, would mechanically reinforce the specimen under the gage area. Likewise, the spring tension of an extensometer would either deform or pre-strain the specimen when sufficient force was applied to prevent slippage between the contact surfaces of the extensometer and the sample. Optical measurement of strain was also unsuitable due to the submersion of the stress–strain apparatus in liquid cryogens for low temperature measurements. Instead, a linear variable differential transformer (LVDT) that connects to the top of the stress–strain apparatus was used to measure strain. The advantage of this technique is that the mechanical properties of the sample are not altered prior to measurements. The disadvantage is that the LVDT measures the total displacement of both the sample and the apparatus. Hence, in order to extract the strain to which the sample is subjected, a determination of the compliance of the measurement system was required.

For this purpose, a stiff stainless-steel sample, 1 mm thick and 5 mm wide, was measured with a strain gage attached to it. The slope of the elastic region of the stress–strain characteristic of this sample was calculated from both the strain as measured with the strain gage and that determined with the LVDT. The difference between the two values of the slope was used to estimate the compliance of the apparatus. The compliance was determined at room temperature, 76 and 4 K, and systematically used to correct all data presented in this work.

Additionally, in order to further minimize the effect of compliance, we use a long sample gage-length of 25.4 cm. This assures that compliance of the sample is very large compared to that of the entire apparatus, and hence guarantees higher precision in the measurement of strain.

A procedure for mounting specimens into the apparatus was developed to avoid work-hardening the delicate substrates (especially pure Ni) prior to measurements. A mounting frame is utilized to align the grips and fix their position while the specimen is soldered. The frame also provides mechanical support to the sample, predetermines the gage length, and aligns the specimen with the load train during the mounting of the sample into the apparatus.

Fig. 1 shows the mounting frame (beryllium–copper solder grips and stainless-steel rods) and stainless-steel dowel pins alongside the tail-piece of the stress–strain apparatus. The beryllium–copper grip fixtures are attached to opposite ends of a pair of stainless steel rods by small set-screws tightened against the rods (shown in Figs. 1 and 2). These rods provide rigid support to the sample against twisting and sagging during mounting, and they also define the prescribed gage length at 25.4 cm. Each end of the sample is soldered into a shallow groove along the centerline of each respective grip. The sample is pressed against the grip surface during soldering in order to expel excess molten solder and ensure a thin solder layer thereby creating a mechanically strong interface between the sample and grips. A mechanically robust solder (96% Sn, 4% Ag) maintains strength at cryogenic temperatures and stands up well to thermal cycling.

Once the specimen is soldered onto the grips, the frame is then positioned in the stress–strain apparatus and attached to the load train with stainless-steel clevis pins at both ends of the frame. Rotational alignment is provided by a Teflon™ block (see Fig. 2) that is free to slip between two support rods on the apparatus. After connecting the mounting frame to the apparatus, the set-screws on the grips are removed and the fixtures are free to move independently of the mounting-frame support rods.

Specimens measured are typically 50–100 μm thick and 30 cm long. Interchangeable grip fixtures allow us to measure tape widths of 4, 5, 10, or 12 mm. The apparatus is connected to a servo-hydraulic actuator equipped with a 1300 N load cell and a LVDT to measure stress and strain, respectively. For measurements at cryogenic temperatures, external stress on the sample from differential thermal con-

Fig. 1. Stress–strain measurement apparatus showing beryllium–copper solder grips and frame for supporting the thin sample tapes during mounting.

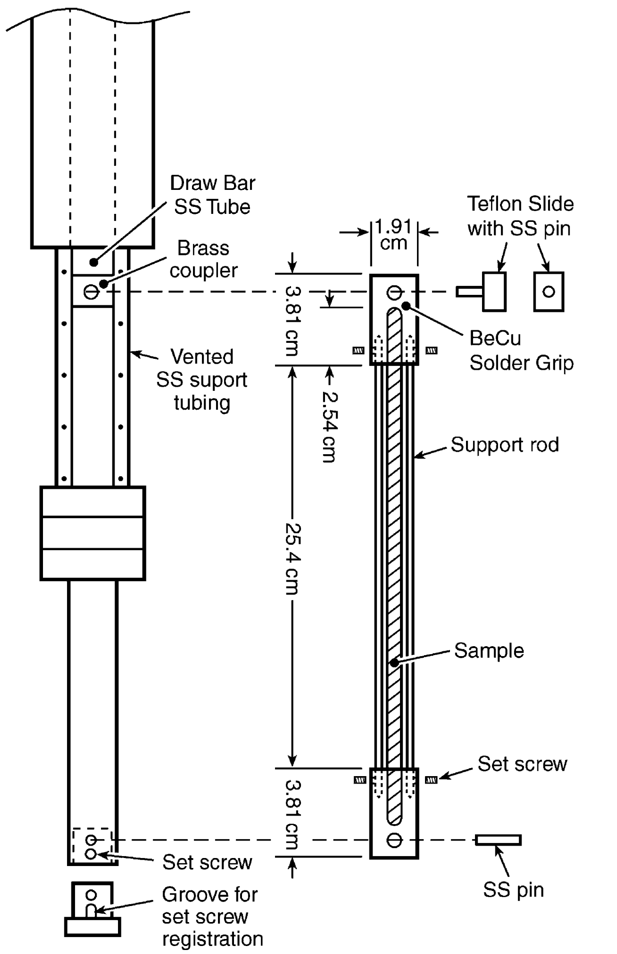

Fig. 2. Schematic diagram of measurement apparatus used for stress–strain measurements at room and cryogenic temperatures.

traction during cooling is automatically compensated by cooling the sample in load control at a small nominal load (2–3 lbs. tensile load). After the sample is cooled and thermally stable, the system is then returned to position control and set to the position where the load is nominally zero. Sample strain is then applied at a rate of 0.02–0.03% strain per second.

The uncertainties in determining the Young's modulus and yield strength for our thin substrate tapes are due mainly to the uncertainties in measuring the tape dimensions, particularly the thickness. This uncertainty is estimated to be about 10%, depending on the variation of thickness along the tape's length.

3. Experimental results

Data obtained on various RABiTS and IBAD conductors are presented in Figs. 3–7, and a comprehensive summary is assembled in Table 1. None of the samples were tested to fracture since the emphasis was placed on determining the Young's modulus, the yield strength at 0.02% and 0.2% offset criteria, and the proportional limit of elasticity.

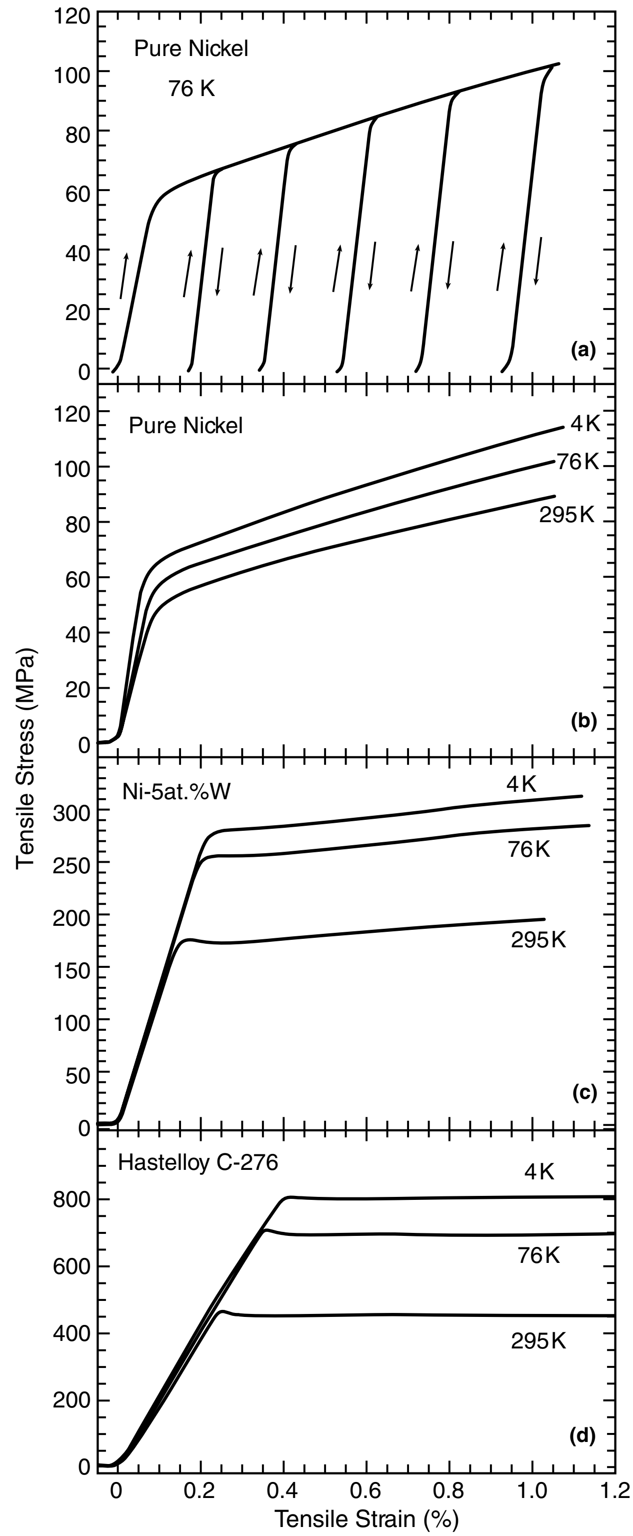

Fig. 3. Representative stress vs. strain data of various substrate materials. (a) Typical data on a pure Ni specimen at 76 K showing the load/unload direction of applied stress. (b–d) Comparisons at three different temperatures for RABiTS materials (pure Ni and Ni–5at.%W) and an IBAD material (Hastelloy C-276).

Fig. 3(a) shows typical stress–strain data, with the arrows depicting the direction of load application. This particular plot shows stress–strain data for a pure Ni sam-

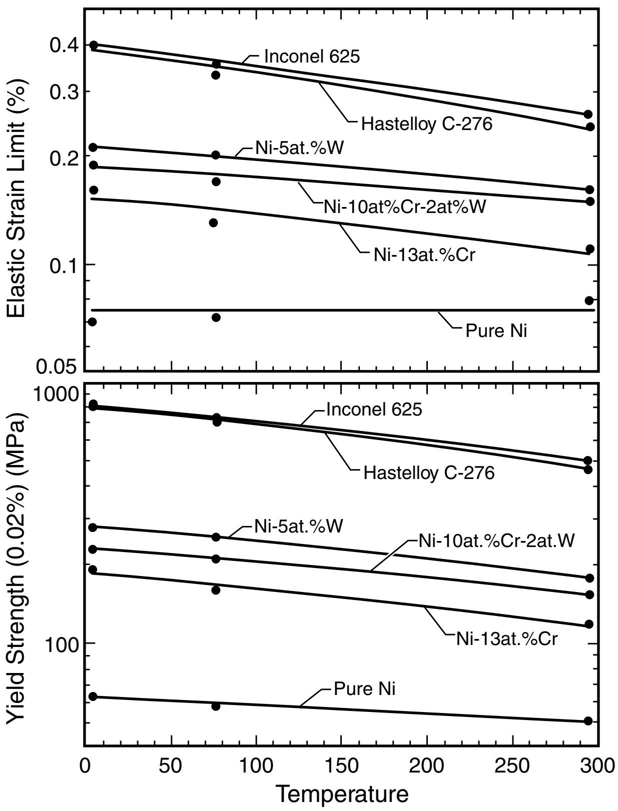

Fig. 4. Temperature dependence of the elastic-strain limit and yield strength (0.02%) for RABiTS and IBAD substrates.

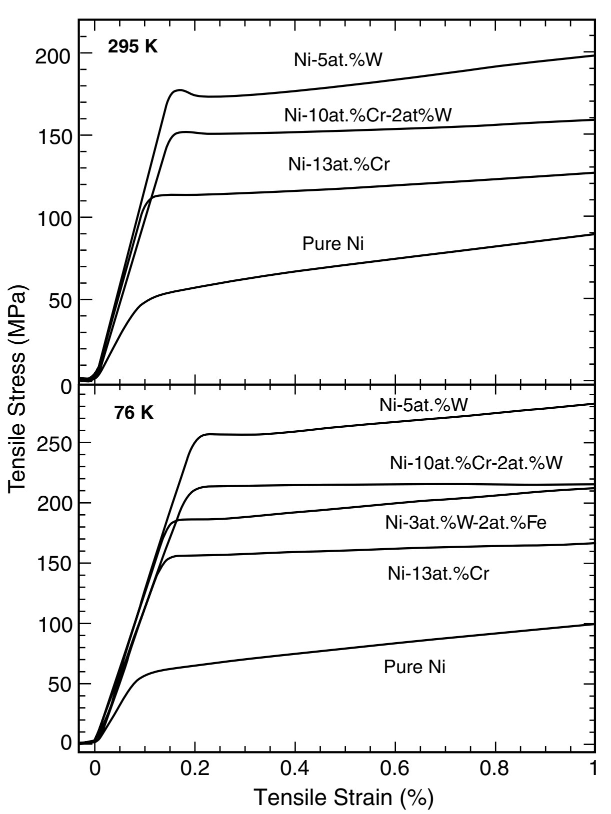

Fig. 5. Tensile stress vs. strain data comparing various RABiTS materials at 295 K (top) and 76 K (bottom).

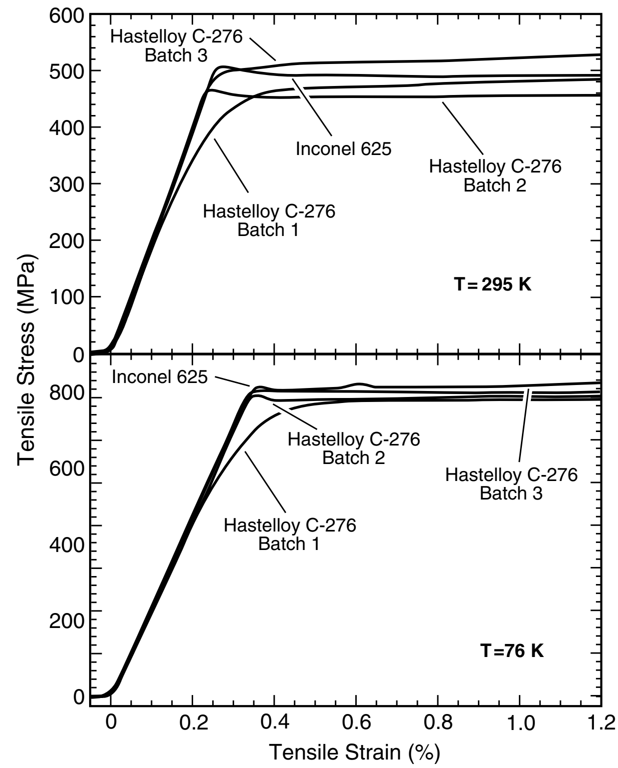

Fig. 6. Tensile stress vs. strain data comparing IBAD substrate materials (Inconel 625 and Hastelloy C-276) at 295 and 76 K.

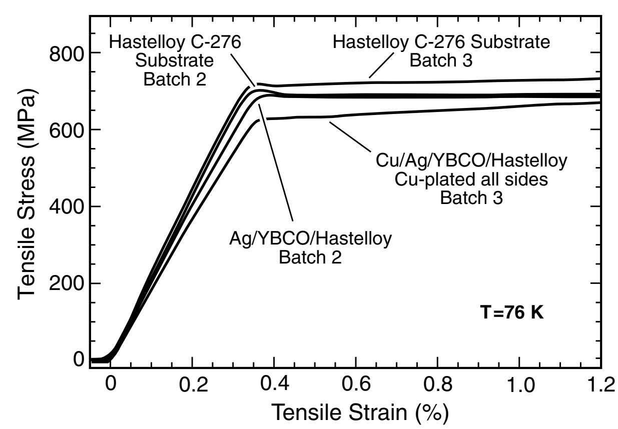

Fig. 7. Tensile stress vs. strain data at 76 K, comparing bare Hastelloy substrates with fully coated Hastelloy IBAD conductors.

ple at 76 K. Pure Ni was the most challenging material to measure due to it's low yield strength and tendency to work-harden. As load was applied to the pure Ni sample, the initial slope of the stress–strain characteristic (Young's modulus) is not clearly definable. At higher strain levels beyond the yield point, the load was slowly released and then reapplied. This unloading-and-loading was repeated periodically up to a strain about 1%. The slope of the unload/load data shows a defined and consistent Young's modulus.

Representative tensile stress vs. strain characteristics are shown in Fig. 3(b)–(d) for various substrate materials at

Table 1
Mechanical properties of substrate materials

	ε_p[a] (%)	σ_Y[b] (0.02 %) (MPa)	σ_Y[b] (0.20 %) (MPa)	E[c] (GPa)
Pure Ni				
295 K	0.08	51	63	60
76 K	0.07	58	71	70
4 K	0.07	64	78	91
Ni–13at.%Cr				
295 K	0.11	118	121	111
76 K	0.13	162	164	112
4 K	0.16	192	194	119
Ni–10at.%Cr–2at.%W				
295 K	0.15	153	154	107
76 K	0.17	210	213	120
4 K	0.19	231	234	124
Ni–3at.%W–2at.%Fe				
295 K	–	–	–	–
76 K	0.14	184	190	128
4 K	–	–	–	–
Ni–5at.%W				
295 K	0.16	177	176	118
76 K	0.20	255	257	128
4 K	0.21	279	283	134
Fully coated conductor: Ni–5at.%W (75 μm thick)/buffer layers + YBCO (≈1 μm)/Ag (≈3 μm)				
295 K	–	–	–	–
76 K	0.16	212	222	132
4 K	–	–	–	–
Inconel 625				
295 K	0.26	499	498	195
76 K	0.36	720	716	207
4 K	0.40	813	813	207
Hastelloy C-276 (Batch 1)				
295 K	0.19	386	464	180
76 K	0.26	599	690	200
4 K	0.34	740	819	199
Hastelloy C-276 (Batch 2)				
295 K	0.24	462	455	195
76 K	0.33	700	693	212
4 K	0.40	798	798	210
Hastelloy C-276 (Batch 3)				
295 K	0.26	508	516	201
76 K	0.34	714	715	214
4 K	–	–	–	–
Fully coated conductor: Hastelloy C-276 (Batch 2) (100 μm)/buffer layers + YBCO (≈2 μm)/Ag (≈3 μm); tape 1 cm wide				
295 K	–	–	–	–
76 K	0.35	687	690	197
4 K	–	–	–	–
Fully coated conductor plus Cu plating all sides (30–40 μm total thickness): Hastelloy C-276 (Batch 3) (100 μm)/buffer layers + YBCO (≈2 μm)/Ag (≈3 μm)/Cu-plating all sides (30–40 μm total thickness); tape 4 mm wide				
295 K	0.26	437	454	168
76 K	0.36	628	640	175
4 K	–	–	–	–

[a] ε_p: Elastic-strain limit.
[b] σ_Y: Tensile yield strength.
[c] E: Effective Young's modulus (initial slope of stress vs. strain).

three temperatures that are relevant to the engineering, fabrication and application of coated conductors. The unload/load data were removed from these plots for clarity.

Fig. 4 shows the temperature dependence of the elastic-strain limit (upper graph) and yield strength (lower graph) plotted in semi-log scale for all of the materials tested. The two IBAD substrate materials, Inconel-625 and Hastelloy C-276, showed comparable elastic-strain limits and yield strength. For the RABiTS materials tested, Ni–5at.%W has the highest elastic-strain limit and yield strength. Pure Ni, on the other hand, yields at strains and stresses many times lower than those of any of the Ni-alloy materials measured. All materials show an increase in yield strength and elastic-strain limit as temperature decreases.

Complete stress–strain characteristics of the different RABiTS materials at room temperature and 76 K are compared in Fig. 5. Again, the graph shows that Ni–5at.%W is the strongest and tolerates the highest strain level before yielding at both temperatures, whereas pure Ni is the softest, yielding at low strain under relatively low stress, less than 50 MPa.

Fig. 6 shows stress–strain characteristics of several samples of each of the two IBAD materials at room temperature and 76 K. Batch-to-batch variations of the same nominal material (Hastelloy C-276) were not insignificant. Batch 1 shows a much lower elastic-strain limit and lower yield strength (0.02%) than batches 2 or 3. However, the yield strength (0.2%) varies less. These differences are evident at both temperatures.

In Fig. 7, a comparison is made at 76 K between bare Hastelloy C-276 substrates and two tapes with various thin coatings typically used in coated conductors. Each conductor used a different batch of Hastelloy C-276, so each fully coated conductor should be compared to its respective bare substrate material batch. Hastelloy (100 μm thick) coated with ≈1 μm YBCO and ≈3 μm Ag shows almost no mechanical difference from its corresponding bare Hastelloy C-276 substrate. On the other hand, the Hastelloy/YBCO/Ag with copper stabilizer plated on all sides (30–40 μm total thickness) shows an approximate 12–14% decrease in yield strength (0.02%) as compared to the respective batch of Hastelloy bare substrate.

4. Discussion

Table 1 summarizes the mechanical properties of the substrate materials and coated conductors tested. The tabulated values are typically averages of three samples in each case, with sample-to-sample variations less than 2% within the same batch of material.

The alloy RABiTS materials show a substantial improvement over pure Ni in their ability to withstand the stress and strain levels associated with coated-conductor fabrication and application. The yield strength of some alloy RABiTS materials rises to well over 200 MPa at low temperatures, more than triple the values measured for pure Ni. These values of yield strength are above application stress requirements. The strain at the proportional limit ranges from 0.1% to 0.2% depending on the temperature and the alloy material. It is important to note that the strain limit for irreversible critical-current degradation is not dictated by the elastic-strain limit of the substrate in YBCO coated conductors, but is two or three times higher [4,11]. The Young's modulus values of the RABiTS Ni-alloys range from 111 GPa to 134 GPa, depending on the particular alloy and temperature, with values at low temperatures being about 7–14% higher than those at room temperature.

Pure Ni RABiTS are a special case. The Young's modulus for pure Ni is considerably lower than that of the Ni-alloys. In fact, determining the Young's modulus of pure Ni RABiTS is difficult because of the very low yield strength of this material. Note that the initial slope of the stress-vs.-strain characteristic in Fig. 3(a) is reduced compared with the slope obtained when the sample is unloaded and then reloaded. We believe that, for pure Ni RABiTS, the unloaded–loaded slope represents the true modulus, whereas the slope on initial loading is an "effective" modulus resulting from material yielding and work-hardening. The unloaded–loaded values are tabulated in Table 1. These values for pure nickel samples textured by the RABiTS process are only about half the handbook values for *untextured* pure Ni. This decrease in the Young's Modulus is consistent with earlier investigations of the effect of texturing in pure Ni [12].

For the IBAD substrate materials, the yield strength (0.2% offset criterion) of annealed Inconel 625 and annealed Hastelloy C-276 are relatively high, ≈800 MPa at 4 K. The discrepancies between Hastelloy (Batch 1) and Hastelloy (Batch 2 and 3) are especially notable, with Batch 1 having a significantly lower yield strength (at 0.02% offset criterion) and elastic-strain limit. The Young's modulus is more consistent, having a value of approximately 200 GPa for all three batches. Values at low temperatures are about 5–10% higher than those at room temperature.

The results at 76 K for fully-coated conductors are also shown in Table 1 for comparison with their respective bare substrate materials for both RABiTS and IBAD conductors. The 75 μm thick Ni–5at.%W RABiTS with ≈1 μm buffer and YBCO, and ≈3 μm Ag coatings has properties similar to that of the bare Ni–5at.%W tape, which indicates that the mechanical properties of composite conductors are dominated largely by those of the substrate. The 100 μm thick Hastelloy IBAD substrate with ≈2 μm buffer and YBCO, and ≈3 μm Ag coatings also differs negligibly from the bare Hastelloy substrate at 76 K, as seen for the Batch 2 results in Table 1 and Fig. 7. However, the Hastelloy IBAD substrate with buffers, YBCO, Ag, and copper plated on all sides (30–40 μm total copper thickness) shows a 12% decrease in 0.02% yield strength and a 10% decrease in 0.2% yield strength at 76 K. The total additional thickness of plated copper is 30–40 μm, thus copper makes up 30% of the composite thickness, yet the drop in the yield strength was only 12%, indicating that the contribution of the copper stabilizer to the overall mechanical properties is not negligible.

5. Conclusion

A database of mechanical properties (at 295, 76, and 4 K) of substrate materials including five RABiTS materials and two IBAD substrate materials is given in Table 1 for coated conductor designs. Sample-to-sample variations for the same batch of a given material were typically less than 2%. However, larger variations were measured from batch to batch for Hastelloy C-276, particularly for the yield properties. The mechanical properties of the fully coated substrate were dominated by the substrate alone, with negligible changes resulting from the addition of relatively thin buffer layers, the YBCO superconductor layer, and the Ag capping layer. The plating of an additional Cu stabilizer layer onto the structure, comprising 30% of the overall thickness, also did not greatly reduce the overall mechanical properties, decreasing the yield strength by only about 12%.

Acknowledgements

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