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# YIELD STRENGTHS OF BIAXIALLY TEXTURED METALLIC SUBSTRATES (Ni AND ITS ALLOYS) DETERMINED USING A SIMPLIFIED TEST METHOD (POSTPRINT)

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A simple testing method is used to compare the yield strengths (YS) of biaxially textured metallic substrates (Ni and its alloys) presently under development for $YBa_2Cu_3O_{7-x}$ coated conductors. This method is based on a retired ASTM D3379 tensile test standard method that was originally recommended for single filament materials. Several common textured substrates, such as Ni, Ni-3at.%W, and Ni-5at.%W, procured from different manufacturers, were tested using this method, and the data were compared with the values reported in the literature. A new alloy substrate (constantan (Cu55-Ni44-Mn1wt.%)) that is biaxially textured in-house was also tested using this method, and the YS data were compared with those of other substrates. For the substrates used in this study, the data obtained using this method indicated that Ni substrates have YS of ~52 MPa, Ni-3at.%W substrates have YS of ~106 MPa, Ni-5at.%W substrates have YS 163 MPa, and Cu55-Ni44-Mn1 wt.% substrates have YS of 74 MPa.

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# Yield Strengths of Biaxially Textured Metallic Substrates (Ni and its Alloys) Determined Using a Simplified Test Method

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A simple testing method is used to compare the yield strengths (YS) of biaxially textured metallic substrates (Ni and its alloys) presently under development for $YBa_2Cu_3O_{7-x}$ coated conductors. This method is based on a retired ASTM D3379 tensile test standard method that was originally recommended for single filament materials. Several common textured substrates, such as Ni, Ni-3at.%W, and Ni-5at.%W, procured from different manufacturers, were tested using this method, and the data were compared with the values reported in the literature. A new alloy substrate (constantan (Cu55-Ni44-Mn1wt.%)) that is biaxially textured in-house was also tested using this method, and the YS data were compared with those of other substrates. For the substrates used in this study, the data obtained using this method indicated that Ni substrates have YS of ~52 MPa, Ni-3at.%W substrates have YS of ~106 MPa, Ni-5at.%W substrates have YS 163 MPa, and Cu55-Ni44-Mn1 wt.% substrates have YS of 74 MPa.

**Key words:** Coated conductors, bi-axial textured metal substrates, Ni and its alloys, yield strength

## INTRODUCTION

Metallic substrates play an important role in the processing of superconducting $YBa_2Cu_3O_{7-x}$ (YBCO)-coated conductors. The substrate is provided with a thin stack of buffer layers onto which a bi-axially textured YBCO layer is deposited.[1–4] Coated conductor technology uses a variety of techniques to meet this texture requirement. For example, a biaxially textured metallic substrate can be used where the substrate texture is transferred through the epitaxial buffer layers to the YBCO layer, the so-called RABiTS™ approach. In the second method, an ion beam-assisted deposition process (IBAD) textures the initial buffer layer deposited on a highly polished untextured metallic substrate that subsequently allows the textured growth of YBCO. So far, several textured metallic substrates have been developed for RABiTS™. They are Ni-based substrates such as Ni, Ni-W, Ni-Cr,[5–9] etc. and Cu-based[10–13,] such as Cu, Cu-Fe, Cu-Ni, etc., with very good biaxial texture. Substrates for the IBAD process are polycrystalline Hastelloy™, Inconel™, or stainless steel. Lattice match, texturability, and compatibility with buffer layers are important criteria in the selection of the textured substrates in the RABiTS™ process. In addition, good mechanical strength and low cost are also of considerable importance.

The yield strengths (YS) of different Ni based alloy textured substrates have been determined by several groups[5–8,14–19], using conventional methods with special sample holders. Experimental differences such as the material differences, thermomechanical processing differences, form of the samples used in testing (rods versus foils), sample preparation methods (cutting versus laser machining), and the mounting methods used to load the samples in the tensile testing machine can and do influence the data as evidenced in the differing

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values found in the literature. For example, the YS data of textured Ni tapes have been reported to be anywhere from 34 MPa to 63 MPa[17,19] when measured at room temperature, probably due to variations in the materials.

Since a less expensive textured substrate can lower the cost of the coated conductors, there is a need to identify these alternative substrates. Traditional ASTM methods (ASTM E8 and E345) for sheet metals require large sample sizes that are hard to produce. Bonded strain gages are not practical, because the gage compliance of the polymer backing can be stiffer than the substrate tapes. A simplified method for quick evaluation of tensile properties is very useful in research and development of alternate textured substrates. In addition, numerous intermediate tests of the samples annealed at different temperatures may be required to identify a suitable annealing treatment to develop texture without significantly reducing the YS. In this study, a simple method was used to determine the YS of textured Ni alloy substrates. The YS data are of greater importance than the ultimate tensile strength (UTS) data for the coated conductor applications as any plastic deformation of the tape during the handling can induce strain in the oxide buffer and YBCO layers, resulting in cracking of the layers. Although this method was described earlier for lower yield strength Cu alloy substrates,[20] this work shows that this method can be extended to higher strength Ni alloys as well.

## EXPERIMENTAL

In this work, commercially available textured Ni alloy substrates as well as in-house textured constantan (Cu55-Ni44-Mn1wt.%) samples were used for YS comparison. The tape samples were analyzed by X-ray fluorescence (XRF) to confirm the chemical compositions. A retired test method for tensile strength and Young's modulus for high-modulus single-filament materials (ASTM D3379) was used as a basis for the tensile strength tests primarily to minimize handling and testing setup damage to thin tapes, and to quickly measure YS strength. This method was used initially for Cu-based textured substrates as discussed elsewhere.[20] Though ASTM D3379 was retired due to inactivity, its test methodology is valid. Bi-axially textured pure Ni and Ni-3at.%W, Ni-5at.%W substrates were obtained from the manufacturers. The presence of biaxial texture was determined by using (111) X-ray phi and (100) omega scans. The full width half maximum (FWHM) values were obtained by fitting a curve through the data points. Ni and Ni-3at.%W, Ni-5at.%W biaxially textured substrates were cut with different gage lengths (7, 22, 28.5, 35 mm) and then annealed at 950°C for 2 h in $Ar/H_2$ to reduce the edge hardening effects due to the cutting of the tapes.

Constantan (Cu55-Ni44-Mn1wt.%) samples were thermomechanically processed in-house from a constantan rod supplied by Goodfellow (10 cm long, 9 mm diameter). The discussion on texture development and other properties of these substrates is reported elsewhere.[21] Briefly, as-received rod was rolled several times with a 10% reduction per pass to a final tape of thickness 50 $\mu$m. The rolled tape was cut into 3 mm wide tapes of different lengths (22, 28.5, 35 mm) and then annealed at 1200°C for 2 h in an $Ar/H_2$ atmosphere and then furnace cooled. The high temperature treatment was necessary to develop good biaxial texture. Three different samples, each 3 mm width and around 40–50 $\mu$m thick were tested for each substrate type.

The details of the testing method have been published previously.[12,20] Briefly, the long tape samples were aligned and mounted with epoxy to a cardboard holder with different gage section lengths. The sample in its cardboard mount was then aligned in the wedge tensile grips (Instron Model 2716-015) of an electromechanical screw-driven Instron tensile testing machine (Type A, Model 4486, SN H1955) using a ±1 kN load cell (Instron SN UK881). Without the use of cardboard, the metallic substrate samples cannot be aligned in the grips of the tensile testing machine without introducing uneven strain. Before each test began, the sides of the cardboard were cut away on either side of the gage section to allow the sample to carry the full test load. Load was gradually applied until the fracture occurred. The crosshead rate was 0.508 mm/min and no extensometer or strain gages were used. The load and displacement data provided by Instron were used to generate pseudo stress vs. strain plots. The yield strength was determined by the 0.2% offset strain method as prescribed in ASTM E-8 (standard test method for tensile testing metallic materials). Another tensile testing machine with a different type of grips (Type B, Instron Model 5500R, SN 5500-C7177 with side action pneumatic tensile grip (Model A2-38, SN 999) was also used to test two substrates of Ni-3at.%W and Ni-5at.%W using the same sample mounting method. Figure 1 shows a photograph of a sample mounted in the tensile testing machine before the load was applied. In the present experiments, the maximum tensile load of the tapes was less than 53 N (~12 lbs) relative to the compliance of the ±1 kN load cell. So for the practical purposes, the test system compliance can be assumed to be negligible compared to the compliance of the actual specimen. The strain is measured by the actuator displacement relative to the gage length of the test specimen ignoring the system compliance and so to differentiate it, the strain is called pseudo strain. The determined yield strength by using the 0.2% strain offset is noted as pseudo yield strength.

## RESULTS AND DISCUSSION

Table I gives the biaxial texture data as determined by X-ray phi and omega scans on various

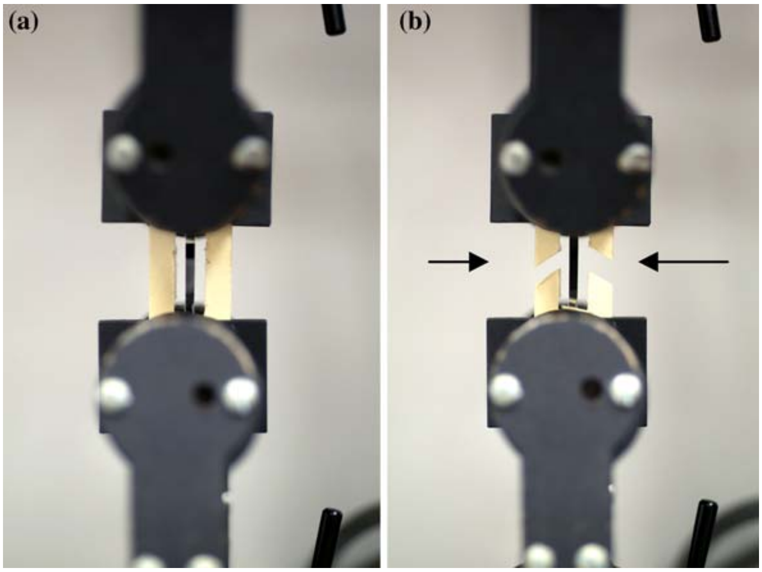

Fig. 1. (a) Textured Ni sample loaded between grips of a tensile strength testing machine using a cardboard holder attached to the sample. (b) Immediately after the alignment, the two sides of the cardboard holder were cut off as shown by the arrows and the load was then applied.

**Table I. Summary of Biaxial Texture Data of the Substrates Used in the Present Study**

| Textured Substrate Composition | FWHM (111) Phi Scan (°) | FWHM (100) Omega Parallel (°) |
|---|---|---|
| Ni | 8.13 | 7.14 |
| Ni-3at.%W | 7.4 | 5.08 |
| Ni-5at.%W | 6.6 | 10.1 |
| Cu55-Ni44-Mn1wt.% (constantan) | 6.5 | 4.9 |

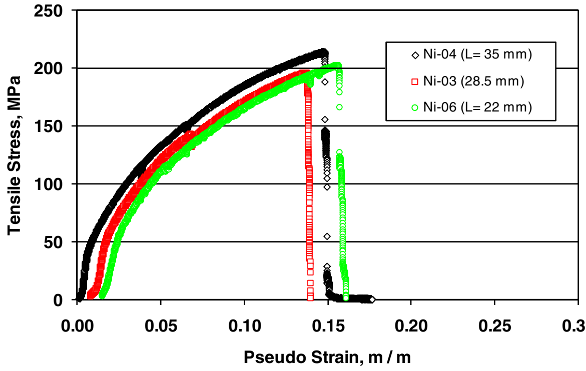

Fig. 2. Pseudo stress–strain plot of all annealed Ni for samples of different gage lengths ($L$).

substrates. It can be seen that the substrates used in this study have good biaxial texture suitable for coated conductor applications with a {111} phi scan FWHM in the range of 6–8 degrees. Figure 2 shows the pseudo stress–strain plots of the three Ni samples of different gage lengths. It can be seen that the load was applied until fracture occurred in the samples. Figures 3 and 4 show the pseudo stress–strain curves of Ni-3at.%W and constantan

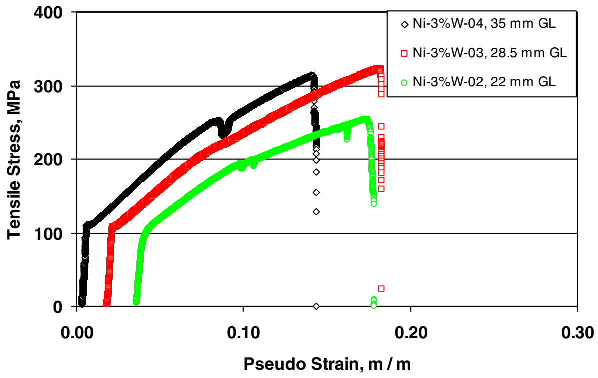

Fig. 3. Pseudo stress–strain plot of all annealed Ni-3at.%W alloy of different gage lengths ($L$).

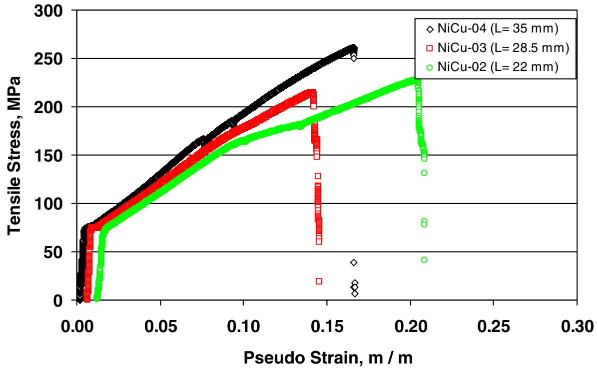

Fig. 4. Pseudo stress–strain plot of all annealed constantan alloy samples of different gage lengths ($L$).

**Table II. Summary of Yield Strength Data of Ni, Ni-3at.%W, and Cu55-Ni44-Mn1wt.% Samples of Different Gage Lengths Obtained Using Type A Instron Machine**

| Samples | Gage Length, mm | Testing Machine | Yield Strength, MPa |
|---|---|---|---|
| Ni samples | | | |
| 1 | 35.0 | A | 46.5 |
| 2 | 28.5 | A | 54.6 |
| 3 | 22.0 | A | 56.3 |
| Ni average ± standard deviation | | | 52.5 ± 5.2 |
| Ni-3at.%W Samples | | | |
| 1 | 35.0 | A | 110.0 |
| 2 | 28.5 | A | 109.0 |
| 3 | 22.0 | A | 98.2 |
| Ni-3at.%W, average ± standard deviation | | | 106 ± 6.5 |
| Constantan Samples | | | |
| 1 | 35.0 | A | 74.9 |
| 2 | 28.5 | A | 74.2 |
| 3 | 22.0 | A | 73.1 |
| Constantan average ± standard deviation | | | 74.1 ± 0.9 |

(Cu55-Ni44-Mn1wt.%) substrates, and similar curve shapes were observed in each batch of the samples as observed in the case of Ni. The average YS data of all the samples in this study are given in Tables II and III. The YS data of textured pure Ni (52 MPa) determined in this study match well with those of the earlier published data of 58 MPa[6] at 0.2% strain.

For the constantan (Cu55-Ni44-Mn1wt.%) samples an average YS of 74 MPa was noted. Although it can be seen that constantan textured samples processed by this method have higher YS than textured pure Ni substrates with YS of 52 MPa, the YS is lower than Ni-3at.%W samples with a YS of 106 MPa. It has been previously reported that constantan substrates annealed at 900°C for 30 min have a YS of 113 MPa.[17] Although the starting materials are different in these two studies, it is possible that the YS of the constantan substrates used in this study was reduced due to increased annealing temperature and time. The Ni-5at.%W substrate was found to have a YS of 163 MPa, which is slightly less than reported values of 176 MPa.[19] This may be due to the differences involved in material and processing methods or perhaps to variations in the test methods.

Figure 5 shows the microstructure of a constantan (Cu55-Ni44-Mn1wt.%) to sample before tensile testing. The sample has an average grain size of 50–100 $\mu$m. All the grains were found to be equiaxed as expected after an annealing treatment. No evidence of exaggerated grain growth or secondary recrystallization was noticed in these substrates, which makes them suitable for coated conductor applications. However, after the tensile testing, a significant change in the microstructure was observed. Figure 6 shows the microstructure immediately after the tensile testing. It can be seen that the strain bands extend over the entire sample area, indicating that slip has occurred over the entire sample width as expected in a single crystal-like microstructure. These slip bands can be seen to exist at an angle to the direction of application of load ([100] direction indicating that the slip has occurred along the {111} planes). The critical resolved shear stress (CRSS) on {111} slip planes of the Cu or Ni (FCC metals) single crystal metal will determine the critical yield strength if the applied load is along [100] crystallographic direction. Although this example shows a severe case of deformation bands

**Table III. Summary of yield strength data of Ni-3at.%W and Ni-5at.%W substrates obtained using Type B Instron machine**

| Samples | Gage Length, mm | Testing Machine | Yield Strength, MPa |
|---|---|---|---|
| Ni-3at.%W | 7.0 | B | 112 |
| Ni-5at.%W | 7.0 | B | 163 |

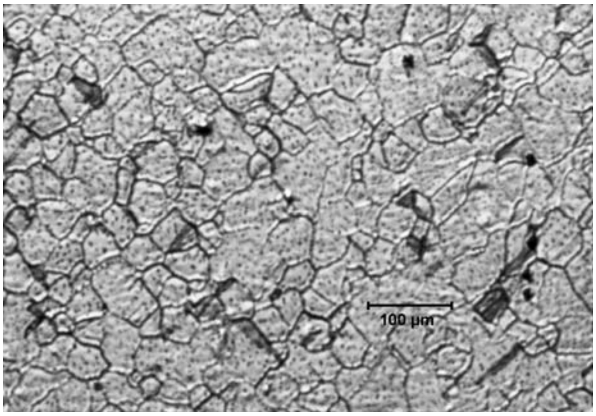

Fig. 5. Optical micrograph showing typical microstructure of an annealed constantan substrate before testing.

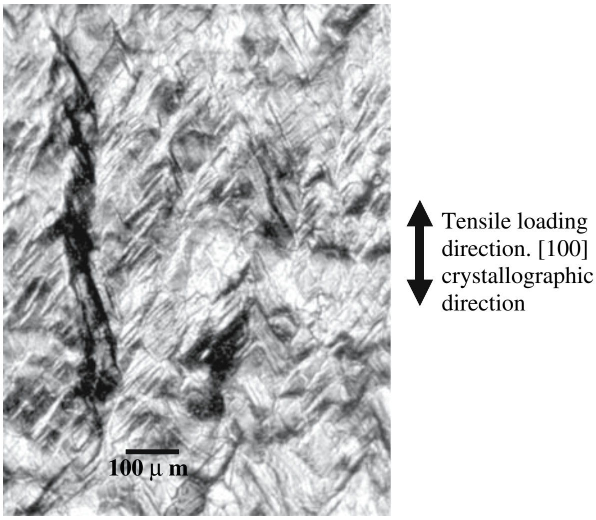

Fig. 6. Optical micrograph of the same constantan sample (as in Fig. 5) after tensile testing. The presence of shear bands at approximately 45 degrees to the loading direction can be seen.

observed (as the sample was tested up to the fracture), similar deformations resulting in Luder band formation are possible in lesser scale in the tapes that are not handled well. Such Luder band formation was also noted in annealed and strained Hastelloy tape substrates by Sugano et al.[22] It is well known that the quality of the YBCO layer depends quite heavily on the underlying buffers layers and the metallic substrate; any such localized deformation can severely affect the current flow along a long length YBCO coated conductor.

The method described above can be extended to other materials of different yield strengths. Testing very high YS substrates may require reducing the sample width so that the load required for the deformation will be reduced. As such, 2 mm may be a more suitable width, which is half of an expected utilization width for applications.

## CONCLUSIONS

The yield strength of Ni-based highly textured metallic substrates such as Ni, Ni-3at.%W, Ni-5at.%W and constantan (Cu55-Ni44-Mn1wt.%) were determined by using a simplified tensile test method developed based on the ASTM D3379 tensile test standard method. This testing method is readily accomplished without the need for a special sample holder and provides a means to compare the yield strength data of different experimental metallic substrates under development for coated conductor applications.

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