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A standardized measurement method and data analysis for the delamination strengths of YBCO coated conductors

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Abstract

Of crucial importance for the application of high temperature superconducting coated conductors (CCs) is the delamination strength due to thermal stress and Lorentz force during their operation. This paper reports the mechanical delamination strengths of YBCO CCs at room temperature and 77 K, as well as the electro-mechanical delamination strength form a modified anvil tensile method. Compared to previous measurement setups, our anvil device only has one degree of freedom of transverse tension. Moreover, we use a vertical soldering technique to ensure the data reliability. Since we eliminate the influence of the measurement method on the experimental results, a naturally discrete property of the delamination strength is obtained. To describe these experimental data, a three-parameter Weibull distribution function has been suggested and a new criterion for determining delamination strength is proposed from the reliability function, which can be conveniently referred to for engineering design.

Keywords: delamination strength, Weibull distribution, YBCO CC

(Some figures may appear in colour only in the online journal)

1. Introduction

Merits of high current density, high critical temperature and high irreversible magnetic field make the state-of-art 2G HTS coated conductors (CCs) preferred candidates for diverse applications in the scaled-up power industry, especially in the application of strong magnetic fields, such as magnets and energy storage, etc [1–3]. In the available manufactoring, various depositing methods, such as the techniques of RABiTS&MOD, IBAD&-MOCVD, IBAD&PLD and IBAD&RCE, etc are used to manufacture CCs [4]. Despite the different adopted fabrication techniques that have been used, these CCs have multilayered structures because of the intrinsic brittle nature of superconducting ceramic, which makes it possible to subject the CCs to some deformation while carrying high currents. However, in practical utilization, thermal stress [5, 6] and Lorentz forces [4, 7], as major stress sources exerted on CCs in the transverse direction lead to critical current (I_c) degradation, these have been found in either epoxy impregnated coils during cooling [8] or paraffin impregnated coils after charging in a strong back magnetic field [9]. Results indicate that the layers between the Ag layer and the substrate layer delaminate and break, which then cause I_c degradation. From the viewpoint of mechanics, the transverse tensile strength of CCs plays an important role in the reliability of both the multilayer structure and electromagnetic behavior. Hence it is important to investigate the transverse tensile behavior of CCs. Since the transverse tensile strength is mainly determined by the adhesion strength between constituent layers, several methods such as the anvil test [10–13], pin-pull test [14], peeling test [15] and cleavage test [16] have been used to research the adhesion strength of CCs. Nevertheless, no universal or reliable method of quantifying adhesion strength exists and the test method needs to be appropriate to the proposed application [17–19]. Among these methods, the anvil

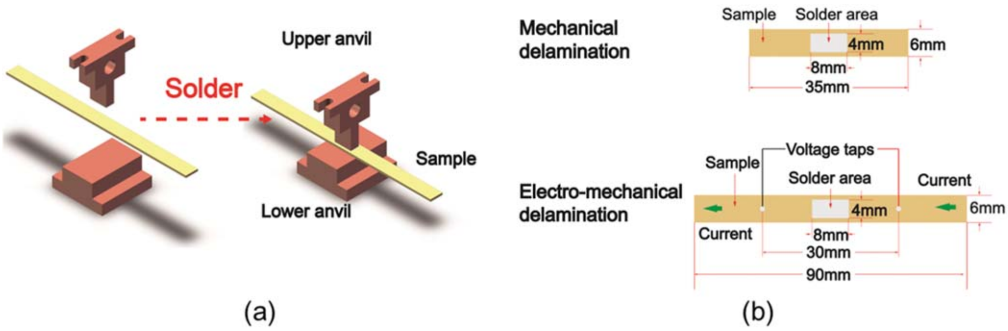

Figure 1. (a) Schematic of anvil test in which sample is soldered between upper and lower anvils. (b) The soldered area is 4 mm × 8 mm in the center of the sample.

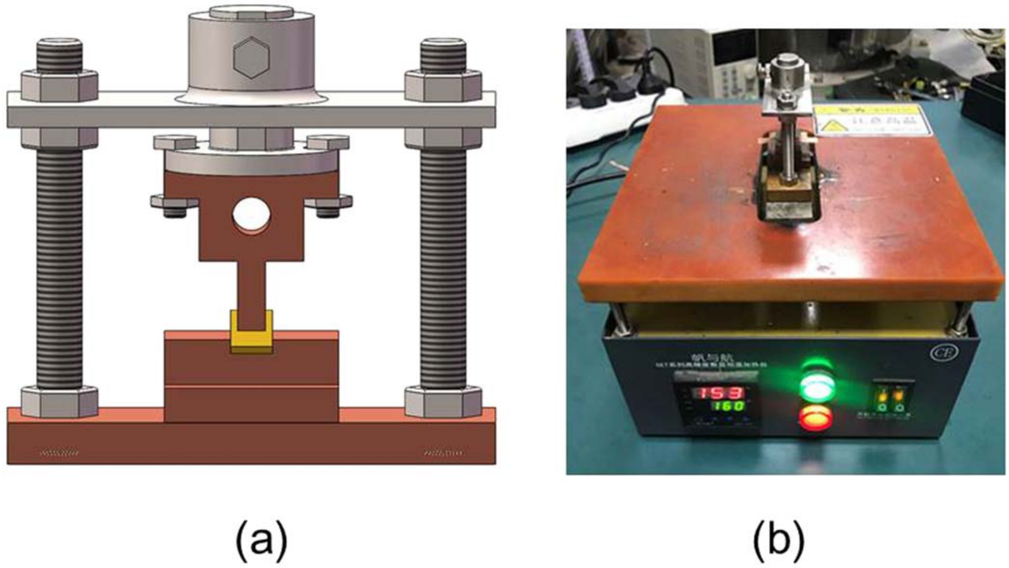

Figure 2. (a) The welding support fixture to keep sample perpendicular to upper anvil. (b) The whole soldering assembly placed on the heating platform.

Table 1. Specification of YBCO CCs samples.

YBCO SCS6050	Fabrication process	Structure	Stabilizer	Manufacturer
6 mm width	IBAD/MOCV2D	Ag/YBCO (1 μm)/LaMnO3/Homo-epi MgO/ IBAD MgO/Hastelloy (50 μm)	Electroplated copper (20 μm)	Superpower

method is the closest to the practical stress type and the easiest to implement for studying the delamination behavior.

The National Institute of Standards and Technology (NIST) first adopted this method and acquired the delamination strength of CCs at 77 K and the critical current behavior under delamination was also discussed [10]. Clear definitions of mechanical delamination strength and electro-mechanical delamination strength were presented by Shin *et al* [11]. In the existing experimental results, both types of delamination strength share two common features. The first is that slitting, as a standard fabricating process, has significant influence on the delamination strength, because damage forms at the tape edges during slitting and cracks are then more easily initiated and propagate from these damage sites. As a result, the delamination strength of a slit sample is less than the original one. To address this problem, several methods are provided, such as adding a solder-laminated additional layer with an edge of solder fillet [10], design of a partially coated conductor [20], or Cu edge reinforcement [21, 22]. The second feature is that all the measured data of delamination strength is exceedingly discrete with the number of testing points increasing. Therefore the average value from those testing points no longer fully represents the true properties of CCs. A study of the microstructure of a delaminated sample found that most fracture occurs within the ReBCO and buffer layers as well as the interface between them [23], indicating that delamination did have characteristics of ceramic fracture, that is the main reason for discrete data of the delamination

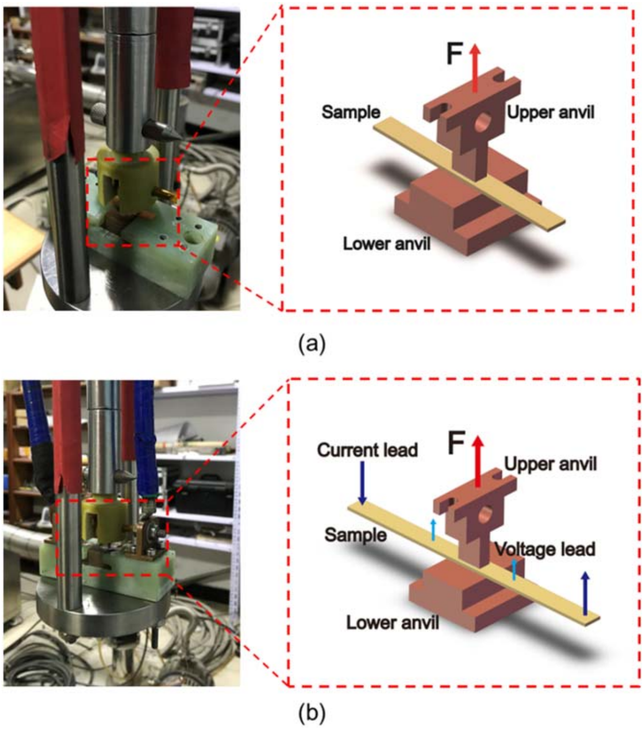

Figure 3. Loading assemblies for different tests: (a) mechanical delamination test for room temperature and mechanical delamination test for 77 K, which is similar to the test at room temperature where a Dewar tank is added and (b) the electro-mechanical delamination test, in which a long sample is used to carry current.

strength. To properly describe the delaminating behavior determined by ceramic strength, a Weibull statistical method can be used, but rare works have adopted this system and the physical meaning for the statistical parameters related to the mechanical properties are still lacking. All in all, the discrete feature of delamination strength of CCs means that the data cannot be directly referenced in engineering design and a criterion should be provided through an appropriate statistical method which fully reflects the properties of delamination of CCs.

In this work, we first report on the devices, including a welding supporting facility and a delaminating test machine; next, the mechanical delamination strengths of a 6 mm width of CC at room temperature and 77 K as well as the electro-mechanical delamination strength are presented; then, the Weibull analysis for three types of delamination strengths are provided; lastly, criterions based on Weibull analysis for these delamination strengths are provided.

2. Experimental methods

2.1. Sample

The YBCO CCs used for this study are SCS6050 bought from SuperPower Inc. The YBCO layer was deposited using the IBAD&MOCVD technique. All the samples used have a width of 6 mm. Table 1 shows the specification of the samples used in this study.

2.2. Sample soldering

Before the anvil test, the samples need to be soldered between the upper anvil and the lower anvil, as shown in figure 1(a). In order to avoid the influence of micro cracks that were introduced by the slitting of the production process on the delamination strength test, the size of the upper anvil was selected to be 4 mm × 8 mm, with the width of the upper anvil slightly narrower than the width of the tapes (6 mm), as shown in figure 1(b).

It should be noted that the alignment between the upper and lower anvils must be carefully kept constant, because any misalignment would cause a bending moment to be exerted on the sample surface. Here we designed a welding support fixture , as shown in figure 2(a), consisting of two screws to ensure the parallel plane of the surface of upper anvil against the lower anvil and a cylinder with a groove in the center of the upper plate has only one degree of freedom to move up and down. Before soldering, the oxide layer on the surfaces of the upper and lower anvils were removed by sandpaper with an average particle diameter of 15.3 μm, and then ALPHA CVP-520 97In–3Ag solder with the melting point of 140 °C was filled between the surfaces of the anvils and the sample. After that, the whole soldering assembly was placed on the heating platform until the solder melted and the temperature of the platform was kept to 160 °C for 5 min, as shown in figure 2(b).

2.3. Mechanical delamination strength and electro-mechanical strength measurements

When the soldered entirety of the anvils and sample cooled naturally, it was taken out from the soldering assembly and then assembled in a universal material testing machine, as shown in figure 3.

In the loading assembly, the upper anvil was connected with an upper loading rod using a plug, and the lower anvil was inserted into a G-10 base of glass epoxy that fixed to the lower loading frame. In the mechanical delamination test the displacement is controlled at a ramp rate of 0.1 mm min^{-1}. The mechanical delamination strengths were acquired when a sudden drop of load from the force–displacement curve occurred, as shown in figure 4(a). The mechanical delamination strength is defined as

$$\sigma = \frac{F_{\max}}{S}, \tag{1}$$

where $F_{\max}$ is the maximum force in the force–displacement curve and S is the soldering area.

In the electro-mechanical delamination test, the force is controlled at a step of 2 MPa. Data of current against voltage in each force testing point was collected and the critical currents, using the criterion of 1 μV cm^{-1}, versus applied stresses were acquired. The electro-mechanical delamination strength is then defined as

$$\sigma = \frac{F\,(I_{c\text{-}remain} = 95\%I_c)}{S}, \tag{2}$$

where $F\,(I_{c\text{-}remain} = 95\%I_c)$ is the force at which the I_c retains 95% of its original value, as shown in figure 4(b).

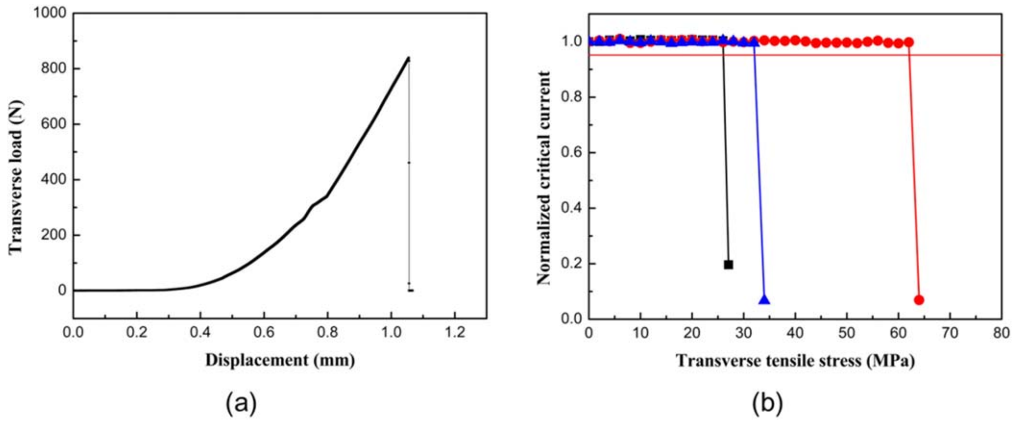

Figure 4. (a) Load-displacement curves obtained under transverse tensile loads. The curves defined the mechanical delamination strength of CC tapes. (b) Normalized critical current as a function of the transverse tensile stress applied to CC tapes, which defined the electro-mechanical delamination strength.

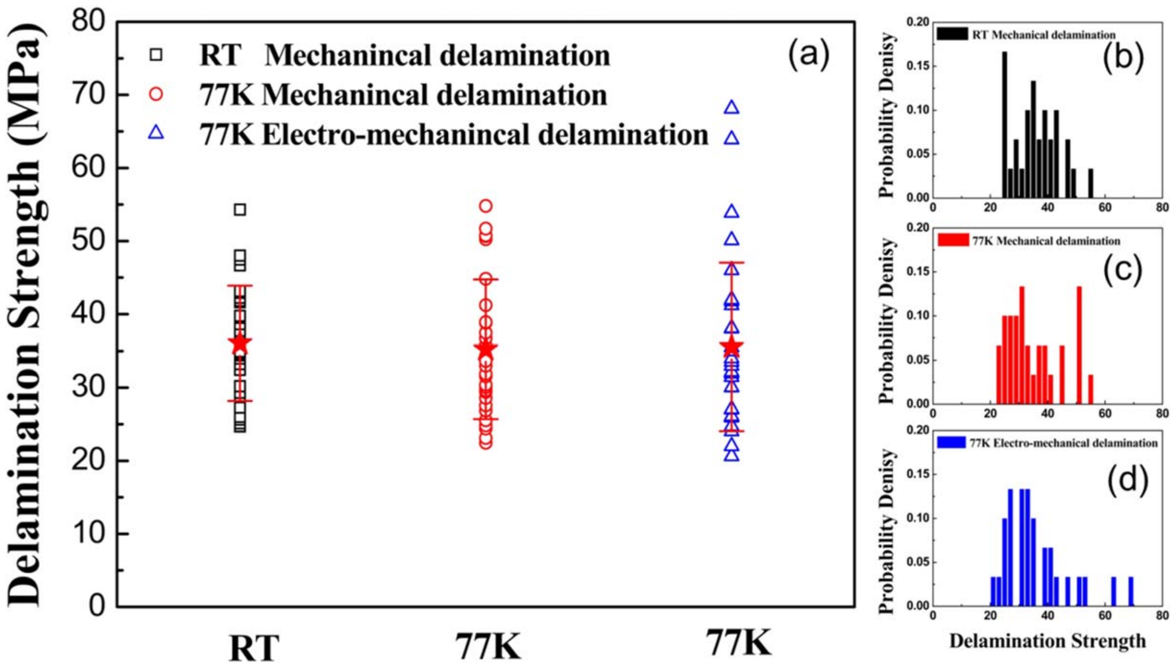

Figure 5. Delamination strength of YBCO CCs in different situations: (a) The black marks indicate the mechanical delamination at room temperature, the red marks indicate the mechanical delamination at 77 K and the blue marks indicate the electro-mechanical delamination at 77 K. The frequency distribution of delamination strength of YBCO CCs in different situations: (b) the mechanical delamination at room temperature, (c) the mechanical delamination at 77 K and (d) the electro-mechanical delamination at 77 K.

3. Results and discussion

3.1. Delamination strengths of YBCO CCs

In each group test, 30 samples were continually cut and used for testing. Figure 5(a) shows the results of the delamination strengths of YBCO CCs. One can find the mechanical delamination strength ranges from 22.5 MPa to 54.8 MPa, with an average value of 35.3 MPa at 77 K and from 24.7 MPa to 54.3 MPa with an average value of 36.0 MPa at room temperature. The electro-mechanical delamination strength has the maximum of 68.1 MPa, minimum of 20.6 MPa, and mean value of 35.5 MPa. It can be observed that all the experimental results seem to not have a significant difference on the average value and share discrete characteristics.

From the frequency distribution of delamination strength of YBCO CCs as displayed in figures 5(b)–(d), the wide dispersed data of delamination strength of YBCO CCs cannot be described effectively by a normal distribution. The reason for this is attributed to the aforementioned brittle fractures, a common characteristic of ceramics, rather than experimental error or non-uniform properties of the samples. Therefore, in order to evaluate the properties YBCO CCs, Weibull analysis is often adopted.

3.2. Weibull analysis of delamination strengths

Here, a three-parameter Weibull distribution function [24] is used and expressed as:

$$F(x;\, \alpha,\, \beta,\, \gamma) = 1 - \exp\{-[(x - \gamma)/\alpha]^{\beta}\}, \tag{3}$$

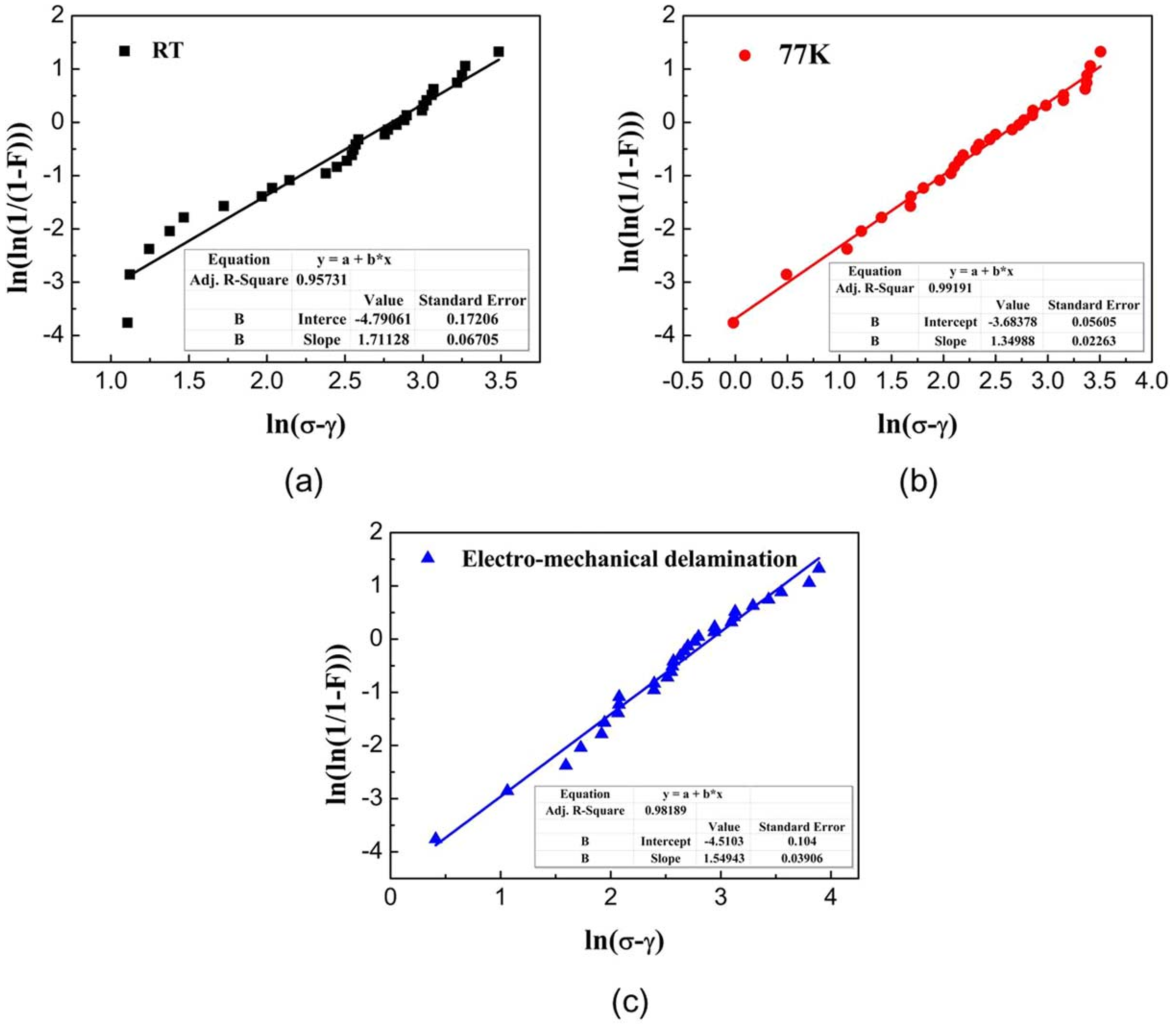

Figure 6. The three-parameter Weibull distribution of the delamination strength of YBCO CCs in different situations: (a) the mechanical delamination at room temperature, (b) the mechanical delamination at 77 K and (c) the electro-mechanical delamination at 77 K.

where x is variable and α, β, and γ are the scale, shape, and location parameters. They are determined from the experimental data using linear regression.

From equation (3) the Weibull reliability distribution function is

$$R(x) = \exp\{-[(x-\gamma)/\alpha]^{\beta}\}, \tag{4}$$

which describes at a given stress how big the possibility of safety is.

Taking double logarithms on both sides of equation (3)

$$\ln \ln\left[\frac{1}{1-F(x;\,\alpha,\,\beta,\,\gamma)}\right] = \beta\ln(x-\lambda) - \beta\ln(\alpha). \tag{5}$$

The function $F(x;\,\alpha,\,\beta,\,\gamma)$ is determined from the experimental data using the Bernard's median rank

$$F(x_i;\,\alpha,\,\beta,\,\gamma) = \frac{i-0.3}{n+0.4}, \tag{6}$$

where x_i is the experimental data arranged from the smallest to the largest, $i = 1$ corresponds to the minimum x_i and $i = n$ to the maximum x_i. $F(x_i;\,\alpha,\,\beta,\,\gamma)$ and x_i are known in this work and the parameters of the Weibull distribution function are obtained by a least squares estimation method using Minitab. Weibull plots of the delamination strengths of YBCO CCs at room temperature and 77 K, as well as the electro-mechanical strength are displayed in figure 6.

One can find that the three-parameter Weibull distribution function can describe the delamination strength of YBCO CCs more effectively, the three parameters in the different situations using the least squares estimation method with Minitab are shown in table 2.

From the results of the Weibull analysis, the physical meaning of the parameters in the distributions are explained as follows: the location parameter γ is the minimum threshold of delamination strength which is the lower limit of delamination strength. This means that the delamination strength of the YBCO would not be lower than the minimum threshold. Hence the location parameter is of great significance to evaluate the transverse mechanical properties of YBCO CCs. The scale parameter γ describes the dispersion of the distribution of delamination strength where a large scale parameter indicates a wide distribution of delamination strength

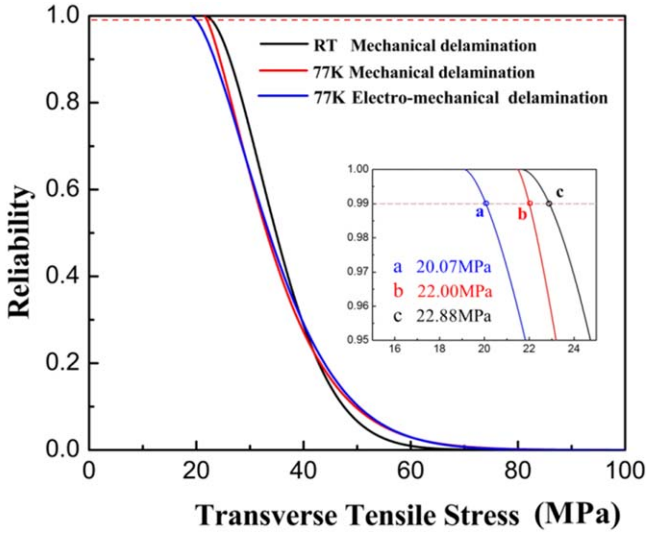

Figure 7. Weibull reliability distribution versus transverse tensile stress. The distribution shows the reliability of the safety of samples under the transverse tensile stress.

Table 2. The three parameters estimated by the least squares estimation in different situations.

Temperature	α	β	γ
Room temperature	16.21	1.78	21.66
77 K	15.26	1.36	21.48
Electro-mechanical delamination	18.26	1.56	19.11

and a small scale parameter indicates a narrow distribution of delamination strength. One can find the distribution of mechanical delamination strength at 77 K is more concentrated when compared to the other two delamination strengths. In general, different types of failure have different β, the shape parameter describes the failure rate when $\beta > 1$ (such as 1.3 and 1.7), indicating an increasing failure rate over transverse tensile stress.

The determined Weibull parameters also uniquely define the reliability of the safety of samples. Figure 7 plots the reliability as a function of the transverse tensile stress, the black line represents the mechanical reliability of YBCO CCs at room temperature, the red line represents the case at 77 K and the blue line represents the case of electro-mechanical reliability. The reliability of transverse tensile stress is very useful for engineering design, at a given possibility of reliability, such as 99%, the corresponding mechanical strengths at room temperature and 77 K are 20.07 MPa and 22.00 MPa respectively and the electro-mechanical delineation strength is 22.88 MPa.

4. Conclusions

This work adopts a modified anvil method with one degree of freedom of transverse tension and a vertical soldering technique to study the mechanical delamination strengths at room temperature and 77 K, as well as electro-mechanical strength. It is found that a three-parameter Weibull distribution function can well describe the discrete properties of the experimental results in these three scenarios, the physical meanings of the three parameters used are also provided. From the determined Weibull distribution function, a new criterion based on the possibility of reliability is obtained and can be directly referred to for engineering design.

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