

NUMERICAL INVESTIGATION OF RESIDUAL STRESSES IN YBCO/CeO₂/YSZ/CeO₂/Ni ARCHITEXTURED MATERIALS FOR COATED CONDUCTORS

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Abstract- In this study, the stress analysis of YBCO/CeO₂/YSZ/CeO₂/Ni architextured materials under cryogenic conditions was carried out for coated conductor applications. YBCO/CeO₂/YSZ/CeO₂ multilayer films were fabricated on Ni tape substrate using reel-to-reel sol-gel and Pulse Laser Deposition (PLD) systems. The microstructural evolution of high temperature superconducting YBCO film and buffer layers with CeO₂/YSZ/CeO₂ configuration grown on textured Ni tape substrates were investigated by a Scanning Electron Microscope (SEM). SEM observations revealed that crack-free, pinhole-free, continuous superconducting film and buffer layers were obtained by sol-gel and PLD systems. The thermal distribution in the each layer was calculated using the classical lamination theory in the temperature range of 25 to -270°C in liquid helium media. The residual stresses occurred during the manufacturing are neglected therefore, all the residual stresses are assumed to be zero at 25°C. Different thermal expansion coefficients and modulus of elasticity bring about the thermal stresses in the layers.

Key Words- Thermal stresses, YBCO, Buffer layers, Sol-gel, PLD, Lamination theory

1. INTRODUCTION

High temperature superconductors (HTS) such as YBa₂Cu₃O_{7-x} (YBCO) are useful for their ability to carry large amounts of current in high magnetic fields and temperatures above liquid nitrogen or helium without any resistance. HTS conductors can be incorporated in numerous electric power devices, including transmission cables, motors, generators, and transformers. To make use of YBCO in these applications, the critical current (I_c) values at temperatures where nitrogen is liquid, must be increased to several hundred amperes in superconductor corresponding to several hundred meters long. The more direct way to increase I_c is to increase YBCO film thickness while keeping critical current density (J_c) constant [1, 2]. However, it has been shown for Pulsed Laser Deposited (PLD) YBCO films that J_c drops rapidly with increasing YBCO film thickness due to structural defects and residual stresses [1-6]. To illustrate this, even though a 2000 nm thick YBCO film was deposited on buffered metal substrates carrying maximum I_c of 200 A as film thickness increased from 2000 to 4700 nm J_c decreased from X to Y. This result implied that additional YBCO layers did not

contribute to the overall I_c . To confirm this, Foltyn et al. [4] used an ion milling process (Ar monomer ions at 150-300 eV) to remove the top layers of a 3000 and 4700 nm thick YBCO films and examined the electrical performance of the remaining film. They found that the top layers of these originally thick films carried little or no current. When the two thick films (3000 and 4700 nm) were thinned below 2000 nm I_c decreased with decreasing film thickness, reaching zero at a film thickness of about 250 nm [1]. It can be concluded that there is a strong relationship between J_c and film thickness. Due to the fact that an increase in film thickness leads to structural defects such as microcracks and residual stresses, J_c directly drops in YBCO films.

Increase in film thickness is regarded as one of the residual stress formation mechanism. The increase in film thickness is attributed to a decrease of the bonding strength and an increase of residual stresses. Two sources of residual stresses can be considered. One may be called a macroscopic thermal stress that arises due to the mismatch in the thermal expansion coefficient between the film and substrate. The other microscopic stress is due to the deposition methods such as sol-gel and PLD [7].

In order to investigate the role of thickness in residual stress formation in YBCO/CeO₂/YSZ/CeO₂/Ni architected materials, there are methods for calculating the stress components in a multilayer coating system under different loading conditions. These methods are based on the lamination theories. The classical lamination theory is the simplest method for obtaining the stress components in multilayer coating [8]. This theory is used to find the stresses in the composite resin laminates and multilayer coatings.

In the present study, YBCO/CeO₂/YSZ/CeO₂/Ni samples were fabricated using reel-to-reel sol-gel and PLD systems for coated conductor application. YBCO superconducting film and buffer layers with CeO₂/YSZ/CeO₂ configuration were examined by using SEM. Stress analysis was carried out on YBCO/CeO₂/YSZ/CeO₂/Ni architected materials under cryogenic conditions. The thermal distribution in the each layer was calculated by using the classical lamination theory in the temperature range of 25 to -270°C in liquid helium media. Each layer was taken as an isotropic laminate. However, the whole layers can be considered as a composite laminate.

2. MATHEMATICAL FORMULATION

According to the classical lamination theory, the strain component without thermal strain at a point is written as [9],

$$\begin{aligned}\varepsilon_x &= \varepsilon_x^0 + zk_x \\ \varepsilon_y &= \varepsilon_y^0 + zk_y \\ \gamma_{xy} &= \gamma_{xy}^0 + zk_{xy}\end{aligned}\tag{1}$$

where, $\varepsilon_x^0, \varepsilon_y^0, \gamma_{xy}^0$: strains of the mid-plane and k_x, k_y, k_{xy} : curvatures of the multilayered material.

The stress components in a layer is written as,

$$\begin{bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \left[\begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + z \begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix} \right] \quad (2)$$

where, $[Q]$ represents the stiffness matrix for a special orthotropic layer.

Resultant forces and moments acting on layers are obtained by integration of the stresses in each layer through the film thickness, for example,

$$N_x = \int_{-\frac{t}{2}}^{\frac{t}{2}} \sigma_x dz \quad M_x = \int_{-\frac{t}{2}}^{\frac{t}{2}} \sigma_x z dz \quad (3)$$

where t is the total thickness of the layers. The total resultant forces and moments are obtained as,

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\ A_{21} & A_{22} & A_{26} & B_{21} & B_{22} & B_{26} \\ A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\ B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\ B_{21} & B_{22} & B_{26} & D_{21} & D_{22} & D_{26} \\ B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix} \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ k_x \\ k_y \\ k_{xy} \end{Bmatrix} \quad (4)$$

or symbolically,

$$\begin{bmatrix} N \\ M \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon^0 \\ k \end{Bmatrix} \quad (5)$$

where, $|A|$: extensional stiffness matrix for the layers, $|B|$: coupling stiffness matrix for the layers and $|D|$: bending stiffness matrix for the layers. The elements in $|A|$, $|B|$, $|D|$ matrices (as shown in Figure 1) are found as,

$$\begin{aligned} A_{mn} &= \sum_{j=1}^N (Q_{mn})_j (h_j - h_{j-1}) \\ B_{mn} &= \frac{1}{2} \sum_{j=1}^N (Q_{mn})_j (h_j^2 - h_{j-1}^2) \\ D_{mn} &= \frac{1}{3} \sum_{j=1}^N (Q_{mn})_j (h_j^3 - h_{j-1}^3) \end{aligned} \quad (6)$$

where, N :total number of layer in the multilayered material, $(Q_{mn})_j$: element in the $[Q]$ matrix of the j th layer, h_{j-1} : distance from the mid-plane to the top of the j th layer and h_j : distance from the mid-plane to the bottom of the j th layer.

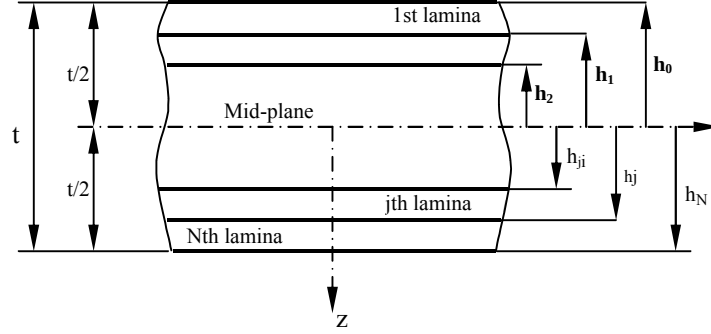


Figure 1. System components

3. THERMAL STRESSES

If a temperature variation is denoted by ΔT in a multilayered material, the resultant forces-strain relations are written as,

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \end{bmatrix} = [A] \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + [B] \begin{bmatrix} k_x \\ k_y \\ k_{xy} \end{bmatrix} - [T^*] \Delta T \quad (7)$$

and for the resultant moments,

$$\begin{bmatrix} M_x \\ M_y \\ M_{xy} \end{bmatrix} = [B] \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + [D] \begin{bmatrix} k_x \\ k_y \\ k_{xy} \end{bmatrix} - [T^{**}] \Delta T \quad (8)$$

where, T^* and T^{**} : thermal resultant forces and moments.

Equation 7 and 8 can be written in a simple matrix form as,

$$\begin{bmatrix} N_x \\ N_y \\ N_{xy} \\ M_x \\ M_y \\ M_{xy} \end{bmatrix} = \begin{bmatrix} A & B \\ B & D \end{bmatrix} \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ k_x \\ k_y \\ k_{xy} \end{Bmatrix} - \begin{bmatrix} T^* \\ T^{**} \end{bmatrix} \Delta T \quad (9)$$

or symbolically,

$$\begin{bmatrix} N \\ M \end{bmatrix} = [C] \left\{ \frac{\varepsilon^0}{k} \right\} - \begin{bmatrix} T^* \\ T^{**} \end{bmatrix} \Delta T \quad (10)$$

The resultant forces N and moments M are zero for a free multilayered material. Then the strain components are found by the inverse manipulation of C matrix as,

$$\begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \\ k_x \\ k_y \\ k_{xy} \end{Bmatrix} = [C]^{-1} \begin{bmatrix} T^* \\ T^{**} \end{bmatrix} \Delta T \quad (11)$$

Then, the stress components are calculated by using the strain components in each layer. They are found as,

$$\begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{66} \end{bmatrix} \begin{bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{bmatrix} + h \begin{bmatrix} k_x \\ k_y \\ k_{xy} \end{bmatrix} - \begin{bmatrix} \alpha_1 \\ \alpha_2 \\ 0 \end{bmatrix} \Delta T \quad (12)$$

where, α_1, α_2 : thermal expansion coefficients in the principal material directions and $\sigma_1, \sigma_2, \tau_{12}$: stress components in the principal material directions.

4. MATERIALS AND METHODS

Prior to coating process, rolled Ni tapes (kindly supplied by Plastronic-Eurus) (0.07 mm x 1.43 mm) were rinsed with acetone. Afterwards, the rolled Ni tapes were annealed at 1150°C for minute under 4 % H₂-Ar flow (10 cc/mm) to obtain texture.

CeO₂ thin film was deposited on textured Ni tapes from solutions derived from Ce based organometallic compounds as first and third layers using the reel-to-reel continuous sol-gel process. Ce-based precursor was dissolved in 100 ml round bottomed flasks using acetylene acetone, and glacial acetic acid as chelating agents. The solutions were consequently diluted with methanol. The above mixtures were stirred for 30 minutes on hot plate maintained at 60°C. Moreover, triethanol amin was incorporated to the solution as a modifying liquid.

Yttria Stabilized Zirconia (YSZ) thin film was deposited on textured Ni tapes from solutions derived from Y and Zr alkoxide as a second layer using the same sol-gel

set up. Y alkoxide was dissolved in 100 ml round bottomed flasks using acetone, and glacial acetic acid. The solutions were consequently diluted with methanol. The mixture was stirred for 30 minutes on hot plate maintained at 60°C. After this process, Zr alkoxide and triethanolamine were incorporated into the prepared solution. This mixture was stirred at room temperature for 4 hours in air.

The textured Ni tapes and buffered Ni tapes were dipped into the solutions at a withdrawal rate of 0.9 cm/sec in a reel-to-reel set up. The precursor films were dried at 300°C for 30 sec and the dried samples were then heat treated at 500°C for 2 min in air in a vertical 3-zones furnace of the same set up. Finally, the films were annealed to density and obtain texture at 1150°C for 10 under 4% H₂-Ar flowing in a horizontal electric furnace. The same procedure was applied to CeO₂ and YSZ buffer layers.

YBCO films were deposited on CeO₂/YSZ/CeO₂ buffered Ni tape by PLD method using a KrF excimer laser ($\lambda = 248$ nm). The substrate temperature was set at about 808°C for 10 min and the oxygen pressure was 100-200 mTorr. The pulse energy density was 225 mJ/cm², and the repetition frequency was 15 Hz. In order to deposit superconducting films on the buffered substrate, YBCO target was used in the present work. The coated superconducting films were annealed at 480°C for 1 hour and subsequently 450°C for 1 hour in order to make them superconductive.

The surface topographies of YBCO/CeO₂/YSZ/CeO₂/Ni, YSZ/CeO₂/Ni and CeO₂/Ni samples were examined by using the ESEM (PGT Princeton Gamma-Tech 540).

Thermal stress analysis was carried out on YBCO/CeO₂/YSZ/CeO₂/Ni sample by using the classical lamination theory in the temperature range of 25 to -270°C in liquid helium media. The multilayered structure is shown in Figure 2. It is composed of five layers such as YBCO, CeO₂, YSZ, CeO₂ and Ni. It is assumed that all the layers are isotropic. The distance between the mid-plane and the layer is denoted by h_j . The mechanical properties of each layer are given at Table 1. It is assumed that the material properties do not change at the decreased temperatures. It is also assumed that residual stresses in the multilayered thin films are negligible at 25°C. The solution of the multilayered material was performed for different temperatures.

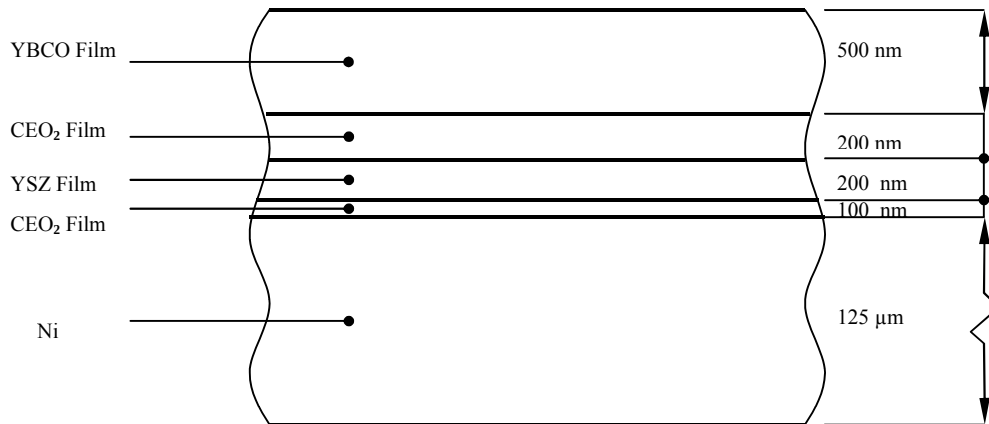


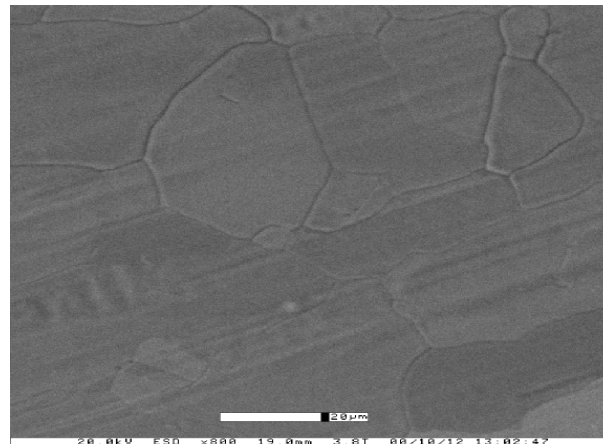
Figure 2. Schematic view of the laminate

Table 1. Mechanical properties of multilayer films [10,11]

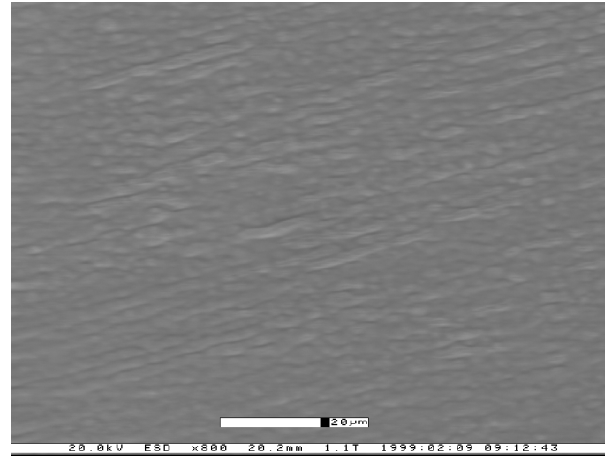
	Modulus of Elasticity E (GPa)	Poisson's Ratio ν	Thermal Expansion Coefficient α ($1/^\circ\text{K}$)
YBCO	180	0.150	14.8×10^{-6}
CeO ₂	165	0.300	11.0×10^{-6}
YSZ	48	0.250	2.2×10^{-6}
Ni	199	0.312	13.3×10^{-6}

5. RESULTS AND DISCUSSION

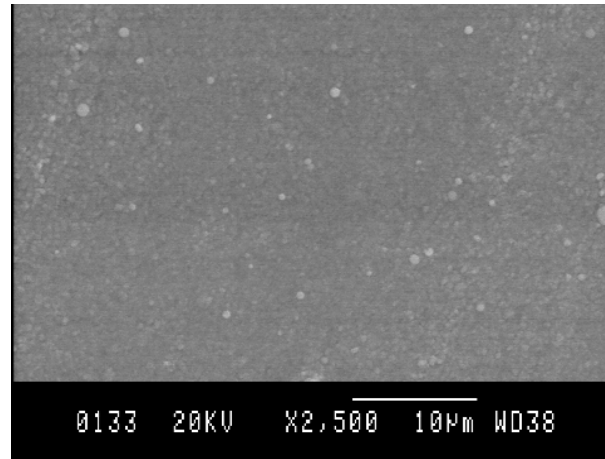
Figure 3 shows surface topographies of CeO₂/Ni, YSZ/CeO₂/Ni and YBCO/CeO₂/YSZ/CeO₂/Ni samples. Crack-free, pinhole-free and continuous CeO₂ and YSZ buffer layers were produced from solutions prepared from alkoxide precursors, solvent, chelating agent and modifying liquid material using reel-to-reel sol-gel technique (see Figure 3a and 3b). SEM examination of YBCO shows a dense microstructure typical of high quality YBCO films deposited by PLD technique (Figure 3c). According to SEM images of CeO₂ and YSZ buffer layers and YBCO, it can be pointed out that there is remarkable difference in their surface morphologies because of fabrication method. Some white particles were observed on the surface of YBCO films deposited by PLD



(a)



(b)



(c)

Figure 3. Surface topographies of (a) CeO_2/Ni , (b) $\text{YSZ}/\text{CeO}_2/\text{Ni}$, (c) $\text{YBCO}/\text{CeO}_2/\text{YSZ}/\text{CeO}_2/\text{Ni}$

The stress component at some temperatures was given in Table 2. As seen in this table, the stress component in YBCO is changing from tensile to compressive in CeO_2 , YSZ, and CeO_2 , because of the different thermal expansion coefficients of the corresponding layers. Since the thermal expansion coefficient of YBCO is the largest one, when they are cooled, it wants to shrinkage and then it applies compressive forces to CeO_2 , YSZ and CeO_2 . As a result of this CeO_2 , YSZ and CeO_2 apply tensile forces to YBCO. Since the thickness of the Ni is much larger than the thickness of other layers, the magnitude of the stress component occurred in the Ni tape is small in comparison with the other layers.

The stress component at 91°K or -182°C, in liquid helium, is 66.45, -111.45, -146.84, and -111.45 MPa for YBCO, CeO_2 , YSZ and CeO_2 respectively. It is 0.94 and -0.47 MPa at the distant points of Ni from the mid-plane. The stress component at 3°K or -270°C, in liquid helium, is 94.7, -158.83, -209.27, -158.84 MPa at the mentioned layers, it is 1.34 and -0.67 MPa in Ni.

Table 2. The Stress component at some temperatures

T (°C)	σ (MPa)					
	YBCO	CeO ₂	YSZ	CeO ₂	Ni	Ni
25	0	0	0	0	0	0
0	8,03	-13,46	-17,73	-13,46	0,11	-0,06
-50	24,08	-40,38	-53,2	-40,38	0,34	-0,17
-100	40,13	-67,3	-88,67	-67,3	0,57	-0,28
-150	56,18	-94,22	-124,14	-94,22	0,8	-0,4
-182	66,45	-111,45	-146,84	-111,45	0,94	-0,47
-250	88,28	-148,06	-195,08	-148,07	1,25	-0,62
-270	94,7	-158,83	-209,27	-158,84	1,34	-0,67

The variation of the stress component through the thickness of layers at -270°C is illustrated in Fig. 4. All the resultant stresses N_x and M_x satisfy the static equilibrium. The variation of the stress component in Ni substrate is small due to largest one which is affected in ignorable values by very thin other layers.

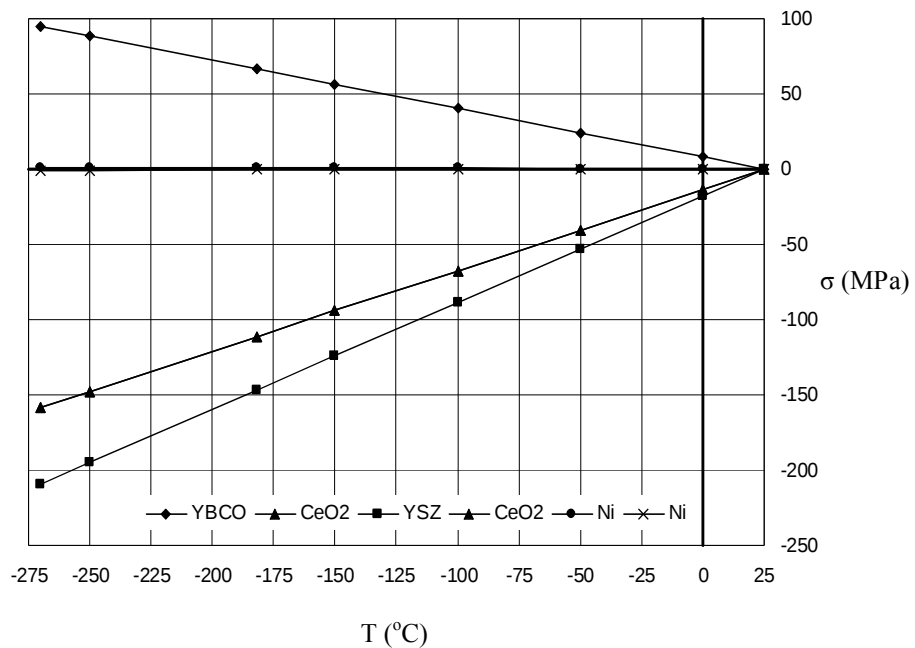


Figure 4. The variation of the stress component in each layer at various temperatures

The variation of the stress component in each layer at various temperatures can be seen in Figure 5. Plastic deformations do not occur at the given temperatures, therefore, the stress component versus temperature changes linearly in each layer.

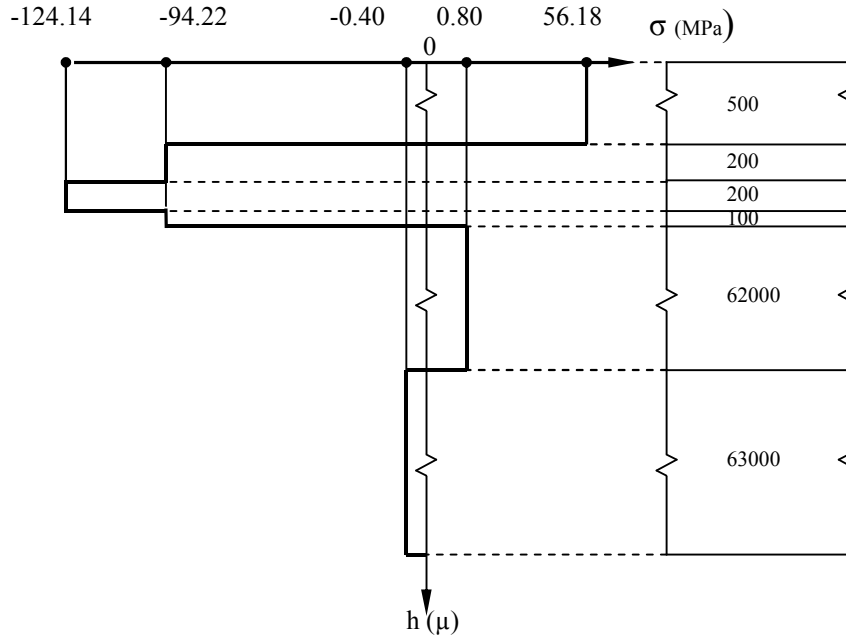


Figure 5. The variation of the stress component through the thickness of laminas at -270 °C

6. CONCLUSIONS

In summary, YBCO/CeO₂/YSZ/CeO₂ multilayer thin films were fabricated on Ni tape using reel-to-reel sol-gel and PLD systems for coated conductor application. Crack-free, pinhole-free and continuous CeO₂ and YSZ buffer layers were produced on textured Ni tape from solutions prepared from alkoxide precursors, solvent, chelating agent and modifying liquid material using reel-to-reel sol-gel technique. YBCO superconducting film with dense microstructure was deposited by PLD technique.

Stress analysis was carried out on YBCO/CeO₂/YSZ/CeO₂/Ni architected materials under cryogenic conditions. The thermal stresses in the multilayer coatings can be calculated by using the classical lamination theory. Different thermal expansion coefficients and modulus of elasticity in the layers produce the thermal stresses during the cooling. The tensile stress occurs in the layers of the largest thermal expansion coefficients. The other layers undergo the compressive stresses. The highest stress component occurs in the very thin sections

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