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Residual stress in the carrier tape AISI 310S at the stage of deposition of the YSZ buffer layer when manufacturing of HTS-2G wire

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Using neutron diffraction we determined internal residual stress in the stainless steel AISI 310S carrier tape with a thickness of 100 μm and a width of 4 mm after mechanical polishing and the ABAD deposition of the textured YSZ buffer layer. It is shown that mechanical polishing causes a slight distension of the tape in the rolling plane. After the deposition of the YSZ layer, uniform tensile stress of 70 MPa isotropic in the rolling plane was observed inside the tape. Calculations have shown that it results from relaxation of compressive stress acting on the surface of the tape in a layer several times thicker than the YSZ layer. It is assumed that the surface of the tape is plastically deformed during the YSZ deposition.

Keywords: residual stress, YSZ buffer layer, HTS-2G wire, AISI 310S carrier tape, neutron stress diffractometry.

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Introduction

AISI 310S stainless steel tape with thickness of 100 μm and width of 4 mm is used as a carrier substrate in the manufacture of HTS-2G wire (Fig. 1) on the experimental process line at the Kurchatov Institute [1]. The wire-making process consists of six consecutive steps:

I. Preparation of the surface of the original steel tape by mechanical polishing.

II. ABAD [2] deposition of a textured yttrium stabilized zirconium dioxide (YSZ) buffer layer about 2 μm thick on the polished steel tape.

III. PLD [3] deposition on the substrate tape with the YSZ buffer layer of additional CeO_2 matching buffer layer less than 0.2 μm thick and the main layer of superconducting ceramic $YBa_2Cu_3O_{7-\delta}$ (YBCO) about 2 μm thick.

IV. Applying a protective layer of metallic silver to the superconducting surface with a thickness of less than 2 μm.

V. Annealing the wire in an oxygen atmosphere.

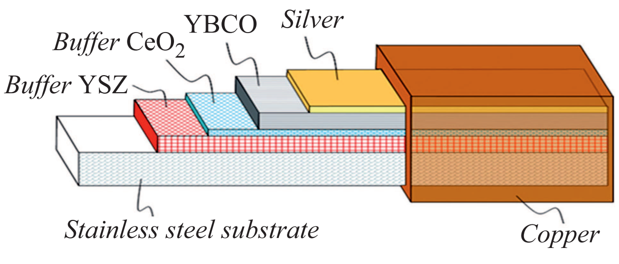

Figure 1. The architecture of an HTS-2G wire manufactured on the experimental process line at the Kurchatov Institute. The figure is taken from [1], the thickness of the steel tape is underestimated by about 20 times.

VI. Coating the wire with a stabilizing layer of copper 10–20 μm.

The strength of the entire HTS-2G wire is provided by the steel tape. Therefore, a change in its physical characteristics at different technological stages is of obvious interest.

Previously [4] the residual stresses in the original AISI 310S tape as deliveried by the steelmaking company were determined using neutron stress diffractometry. This work shows how the distribution of residual stresses changes after mechanical polishing of the tape and after the application of the YSZ buffer layer. The work was performed at the Kurchatov Institute using the neutron diffractometer STRESS [5].

1. Methodological part

The methodology of the experiment is detailed in [4]. Let us mention its main points:

1. Residual stresses in AISI 310S polycrystalline tape are internal macro-stresses which are balanced in the volume of the entire tape. In addition to these, micro-stresses are present in the tape, which are balanced within individual grains and their conglomerations. Macro-stresses affect the positions of diffraction reflections, micro-stresses — their width, shape and intensity.

2. Residual stresses are determined by the strain caused by them. The strain is monitored by the position of the diffraction reflections least affected by micro-stresses. For AISI 310S steel, these are reflections $\{113\}$. The strain is measured on test volumes located inside the sample (Fig. 2). In doing so, it is averaged within each of them.

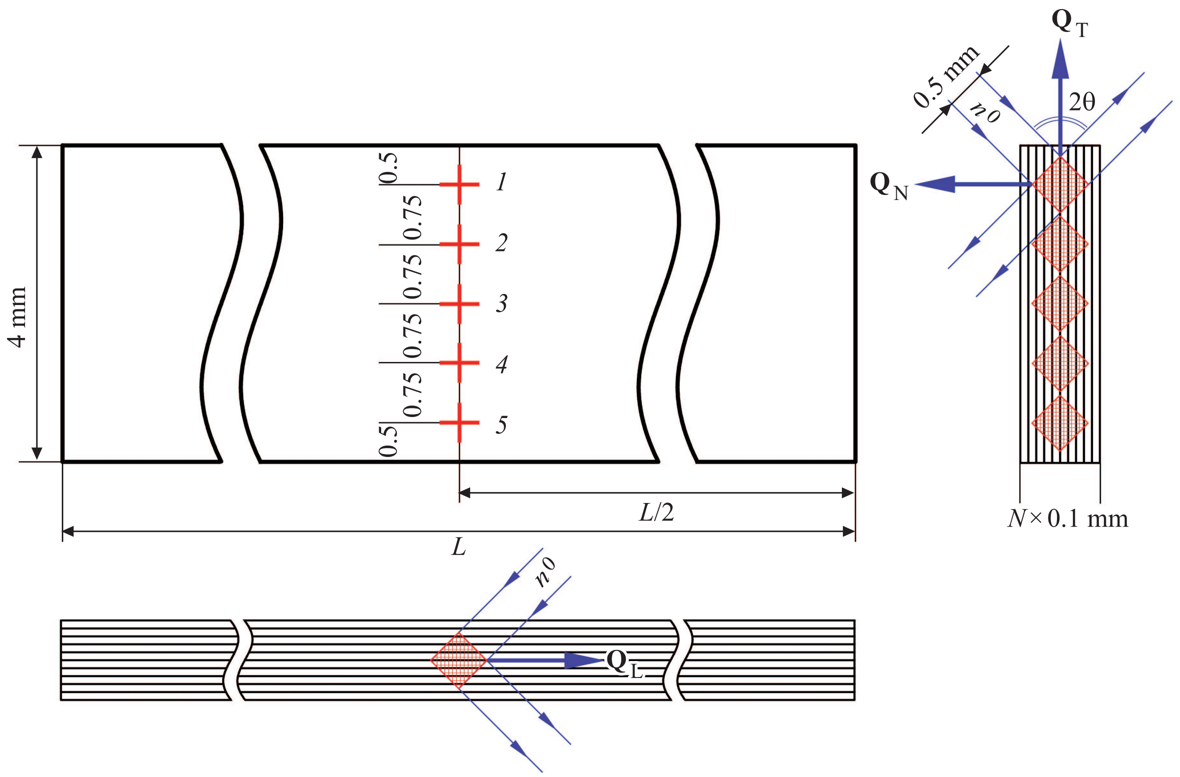

Figure 2. AISI 310S tape sample for neutron stress diffractometry study: a packet of N tape segments with thickness $N \times 0.1$ mm and length L (right — side view, bottom — top view). For original tape $N = 10$, $L = 40$ mm [4]; for polished tape $N = 10$, $L = 60$ mm; for tape with YSZ layer $N = 12$, $L = 40$ mm. Numbered crosses indicate the positions of the measuring points, the distances between the points are shown in millimeters, and the test volumes are shaded. For point 1, there are shown the incident and scattered neutron beams n° ($\lambda = 1.548$ Å), scattering angle $2\theta \approx 91^\circ$ for reflections {113} and scattering vectors $\mathbf{Q}_L$, $\mathbf{Q}_T$ and $\mathbf{Q}_N$ in measuring L, T and N strain components ε (see details in [4]).

3. The relative strain is taken as

$$\varepsilon = \frac{d - d_0}{d_0}, \qquad (1)$$

where d and d_0 — interplanar distances for the reflecting planes {113} in the strained and unstrained states of the tape, respectively. Three strain components ε_L, ε_T and ε_N are measured at each test point, in three mutually perpendicular directions — along (L), across (T) the rolling and along the normal to the tape plane (N). By using generalized Hooke law, the three main components of the residual stress tensor are calculated:

$$\sigma_i = E\frac{(1-2\nu)\varepsilon_i + \nu(\varepsilon_T + \varepsilon_N + \varepsilon_L)}{(1+\nu)(1-2\nu)}, \qquad (2)$$

where E — Young modulus, ν — Poisson ratio, $i = L, T, N$. For AISI 310S steel $E = 200$ GPa and $\nu = 0.27$ [6].

Experiments were carried out on two samples. One is made from polished tape — the original AISI 310S [4] tape, which has undergone several cycles of mechanical polishing at room temperature using aluminum oxide with particle dispersions of 1 and 0.3 μm as abrasive. In result, the tape thickness has decreased by 2–3 μm, which is not significant for a neutron experiment. The other sample is made from the tape with a textured YSZ layer applied. The application was carried out on polished tape using ABAD [2] technology at 50°C for 72 h, the YSZ layer thickness was 2.1 μm. A YSZ layer of this thickness is invisible to neutrons.

The samples were packs of tapes (Fig. 2) made in a similar [4] manner. A single piece of tape was cut into several segments of equal length, which were sequentially stacked on top of each other while maintaining the orientation relative to the rolling direction, and then the assembly was fixed in the aluminum casing. Measurements were made in the same way as in [4], through a layer of aluminum at five points across the width of the tape, positioned midway between the length and thickness of the samples. Cadmium slits with a width of 0.5 mm and a height of 2 mm for the T and N strain components and 0.5 mm for the L strain component were used on the incident and reflected neutron beam.

The determination of the relative strains and residual stresses was carried out in the same way as in [4]. The relative strains were calculated from the measured interplanar distances d for the planes {113}. The value d_0 for the unstrained state was obtained by calculating within

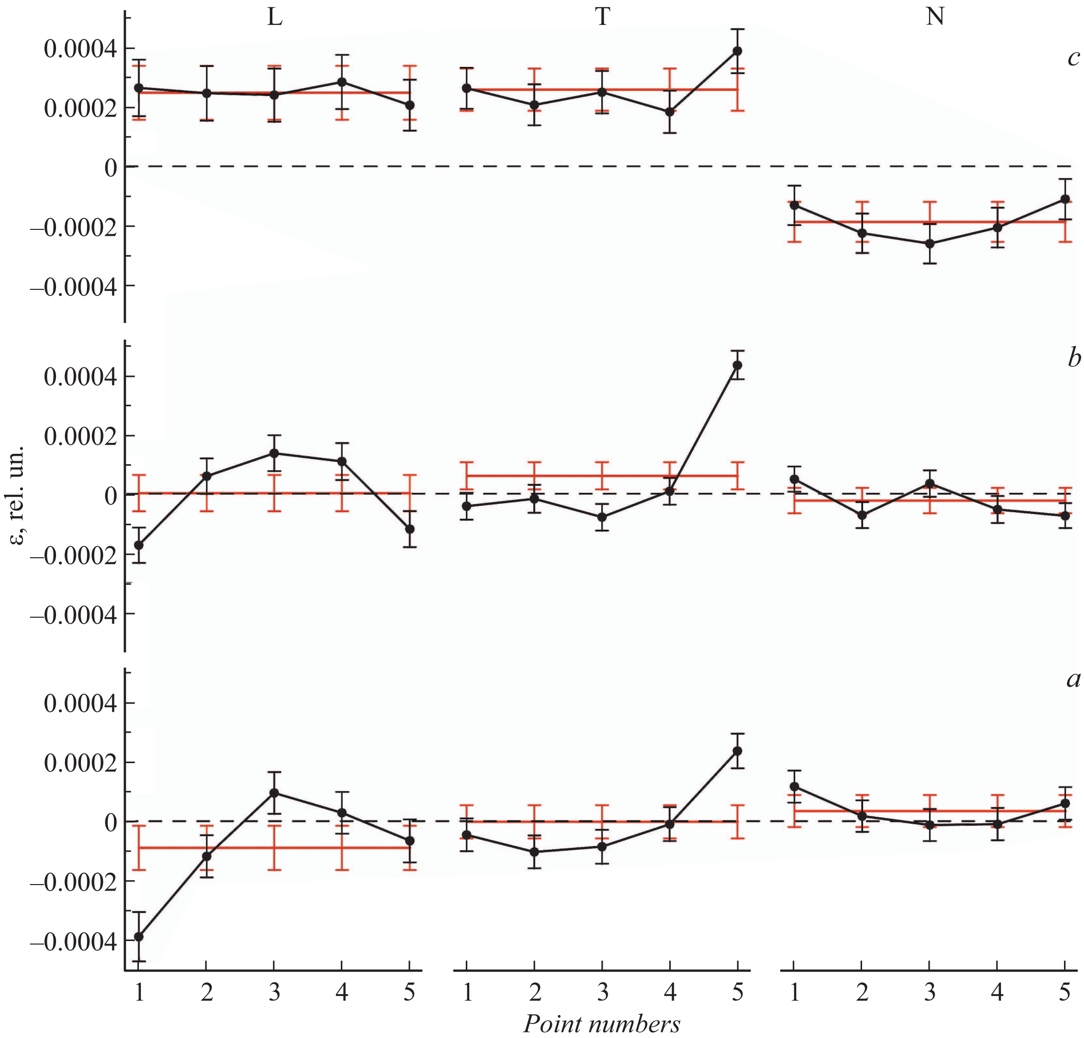

Figure 3. Relative strain ε in the original tape [4] (*a*), polished tape AISI 310S (*b*), YSZ-laminated tape (*c*) at five points across the width (see Fig. 2) in the L-, T- and N-direction. The symbols, connected by lines for clarity, correspond to the experimental values, with the corresponding errors. The horizontal red lines (in on-line version) with the errors plotted are the average strain values $\langle\varepsilon\rangle$ in each direction, the dashed lines show the zero value.

the conventional thin plate model [7] assuming $\langle\sigma_N\rangle = 0$. For all samples, the d_0 values matched within the margin of error: $d_0 = 1.083522 \pm 0.000030$ Å for the original tape [4], $d_0 = 1.083490 \pm 0.000030$ Å for polished tape and $d_0 = 1.083540 \pm 0.000051$ Å for tape with a YSZ layer. Using the corresponding values of d_0 and formulas (1) and (2), the relative strains ε (Fig. 3) and residual stresses σ (Fig. 4) were determined.

2. Results and discussion

There are no significant differences in the distribution of internal strains and residual stresses between the original and polished tapes, and they are mostly within or at the error level (Figs. 3, *a, b* and 4, *a, b*). At the same time, there are some noteworthy details.

Compared to the original tape in the polished tape, the average strain in the plane, $\langle\varepsilon_L\rangle$ and $\langle\varepsilon_T\rangle$, increased slightly and perpendicular to the plane, $\langle\varepsilon_N\rangle$ — decreased (see the horizontal red lines (in on-line version) in Fig. 3). A similar pattern is observed for the residual stresses (Fig.4) with the difference that the normal stress $\langle\sigma_N\rangle$ is initially assumed to be zero. These changes indicate stretching of the tape in the rolling plane. In addition, in the polished tape in the longitudinal direction (L), the residual stress difference at the opposite edges (between points *1* and *5* in Fig. 4) was halved, to 50 ± 45 MPa (versus 100 ± 60 MPa in the original tape), indicating a reduction of sickle deformation [4]. Both effects are naturally attributable to the specific nature of the polishing process. (Polishing is carried out by longitudinal to transverse mechanical action of the polishing head on the tape wound on the drum; the pressure of the head on the tape, and the tape tension on the drum are finite and are set at the start of the process.)

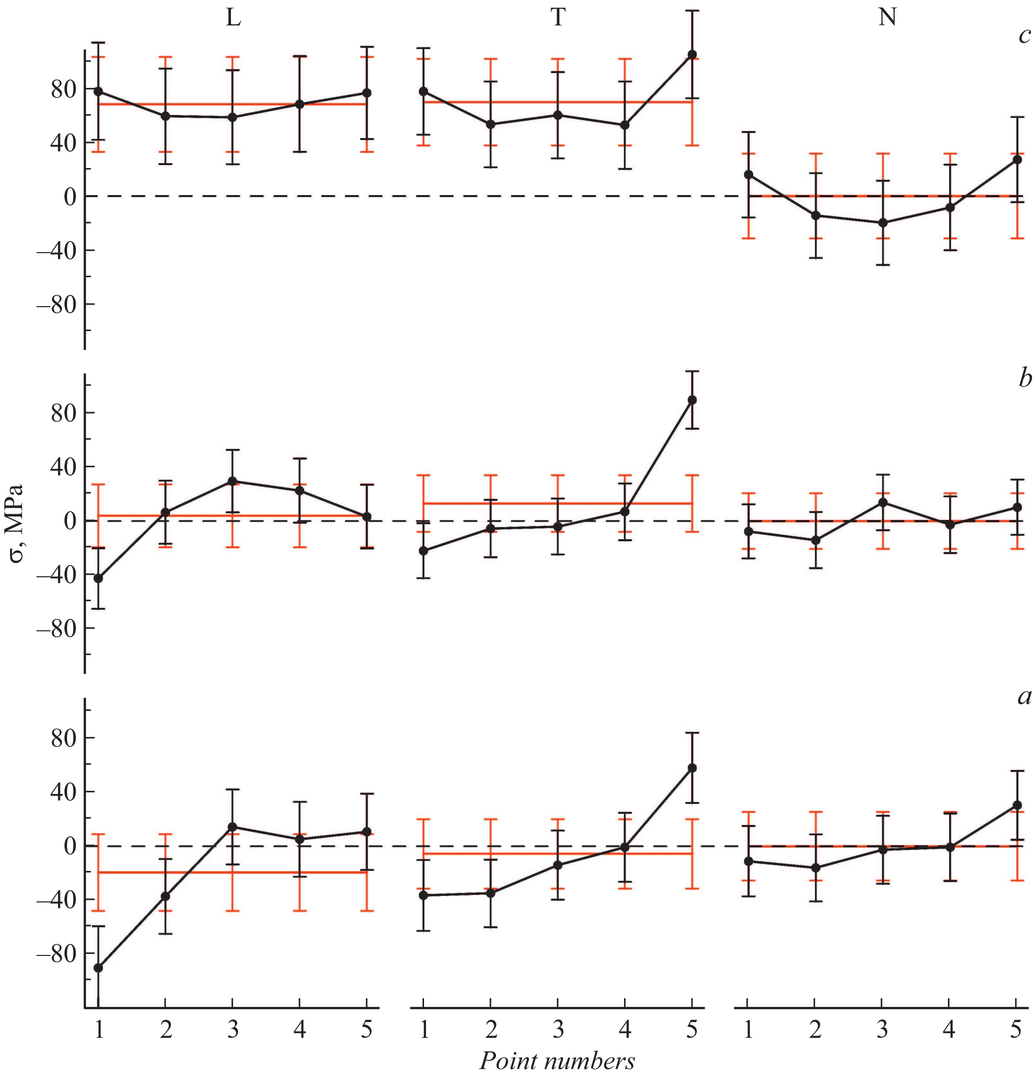

Figure 4. Residual stresses σ in the original tape [4] (a), polished tape AISI 310S (b), YSZ-laminated tape (c) at five points across the width (see Fig. 2) in the L-, T- and N-direction. The symbols, connected by lines for clarity, correspond to the experimental values, with the corresponding errors. The horizontal red lines (in on-line version) with plotted errors indicate the average residual stresses $\langle\sigma\rangle$ in each direction, the dashed lines indicate the zero value.

Another result of polishing is the removal of burrs on the edges of the original tape [4], indicated by the smoothing of the associated excess strain ε_N on the edges (at *1* and *5* in Fig 3, a, b).

The picture changes radically after a layer of YSZ is applied. The longitudinal (L) and transverse (T) strain (Fig. 3, c) and residual stress (Fig. 4, c) components align across the tape width and take the same positive mean values $\langle\varepsilon_L\rangle = \langle\varepsilon_T\rangle = +0.00025 \pm 0.00008$ and $\langle\sigma_L\rangle = \langle\sigma_T\rangle = +70 \pm 35$ MPa, with the normal strain becoming negative $\langle\varepsilon_N\rangle = -0.00019 \pm 0.00007$. This distribution of strains and residual stresses indicates a homogeneous, isotropic stretching of the tape in the rolling plane. As a result of stretching, the original crescent of the tape is greatly smoothed out, but does not disappear completely, as indicated by the persistence of increased transverse deformation ε_T and stress σ_T at the edge (at point *5* in Figs. 3 and 4). The distribution across the tape width of the normal strain ε_N (Fig. 3, c) and residual stress σ_N (Fig. 4, c) is noteworthy. You can see that at the edges the tape is somewhat stretched compared to the central part. A less pronounced similar feature is also observed in the longitudinal (L) and transverse (T) directions. Increased tape stretch at the edges is caused by the same reasons as the overall tape stretch, with a correction for the „edge effect" (see below).

The answer to the question of the causes of plane stretching of the tape after the YSZ layer depositon can be obtained by the following model [8]. If a stressed film, compressed or stretched, is applied to an unstressed substrate, then in the absence of external forces, stress relaxation in the film creates elastic stresses of the opposite sign in the substrate and causes the substrate curvature. The

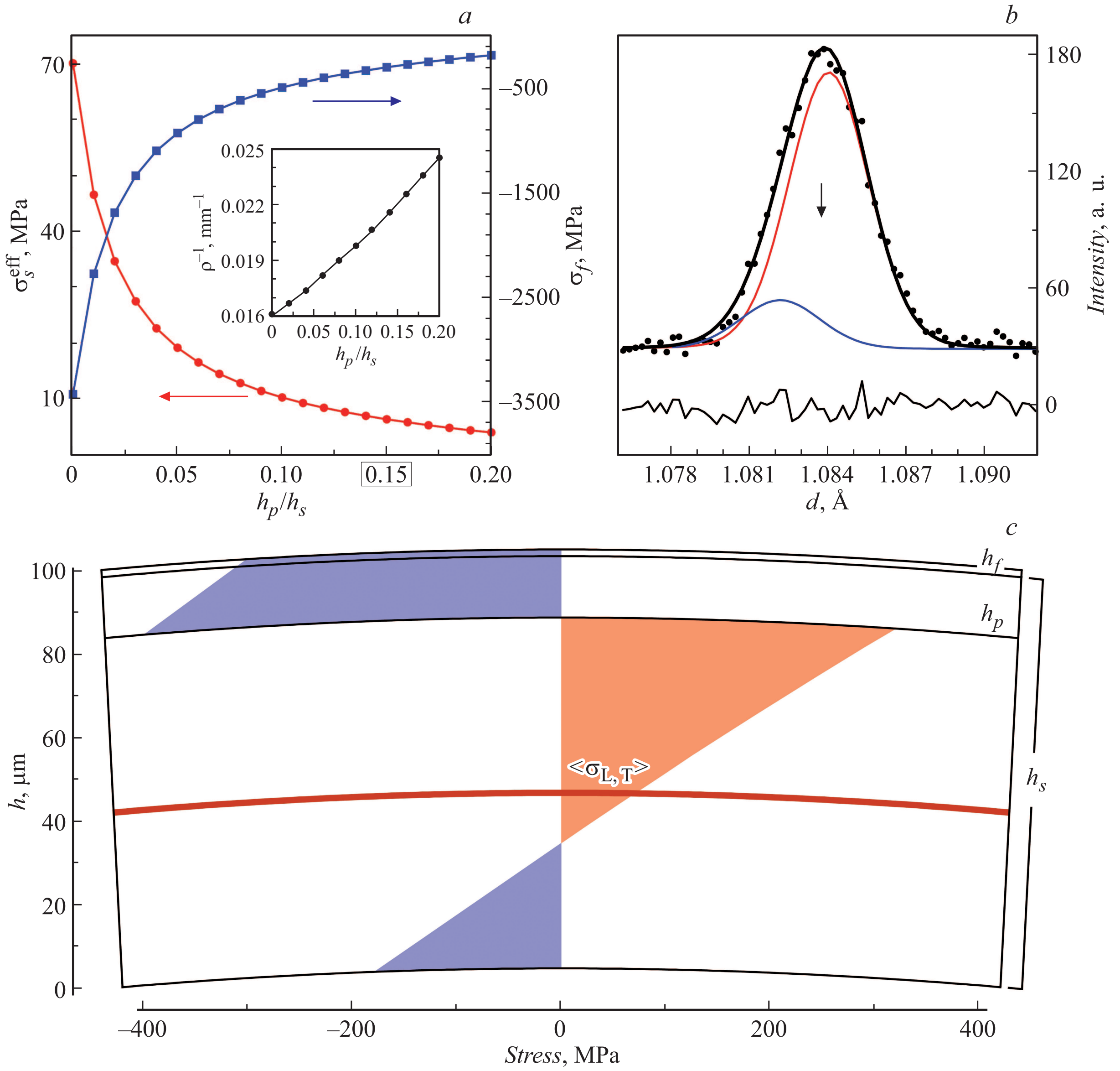

Figure 5. To determination of the elastic (residual) stresses in AISI 310S tape with a YSZ layer (explanation in the text). *a* — the dependence of the effective stress in the tape (σ_s^{eff}) and the stress in the YSZ layer (σ_f) on the ratio of the plastic deformed thickness on the tape surface (h_p) to the total tape thickness (h_s). On insert — change in the curvature of tape, ρ — radius of curvature. The value $h_p/h_s = 0.15$ is marked, for which the following illustrations are given: *b* — experimental (symbols) and fitted (black solid line) diffraction line profile {113} (components of the fitted profile are shown by red and blue lines (in on-line version)), below — difference curve. The experimental profile is averaged profile of the diffraction lines for determination of the transverse strain in the tape (component *T* in Fig. 3, *c*). The arrow marks the center of gravity of the line corresponding to the interplanar distance $d_{\{113\}}$; the thickness of the arrow corresponds to the error of its determination; *c* — elastic stress distribution over thickness *h*, h_f — thickness of YSZ layer. The bold red line (in on-line version) shows the midline of the main, plastically undeformed region of the tape, $h_s - h_p$, where the stress $\langle\sigma_{L,T}\rangle = +70$ MPa is reached. All designations in the figure shown in red and blue (in on-line version) refer to tensile (+) and compressive (−) stresses, respectively.

result will be a balance of forces that depends on the ratio of film to substrate thickness. Since a tape with a YSZ layer is free from external forces, it is natural to assume that its stretching is caused by the relaxation of a biaxial (as in a film) homogeneous isotropic (as inside the tape) compressive stress acting on the surface from the side of the YSZ layer.

The total thickness of the tape with the YSZ layer is around 100 μm, of which only 2 μm is in the YSZ layer. The elastic behavior of AISI 310S steel ($E = 200$ GPa and $\nu = 0.27$ [6]) and YSZ ceramic ($E \approx 200$ GPa and $\nu = 0.26$ [8,9]) are similar. If compressive stresses existed only in the YSZ layer, then, as the balance of forces shows, they would have to be -3430 MPa to create an average stress of $\langle\sigma_{L,T}\rangle = +70$ MPa in the tape. At the same time, in reality, the residual compressive stresses in the YSZ layer determined experimentally for a similar tape ($1\,\mu$m thick YSZ layer deposited by IBAD on $100\,\mu$m thick Hastelloy tape) are an order of magnitude smaller, -365 ± 41 MPa [9].

To reconcile these two facts — the presence of tensile stresses of +70 MPa inside the steel tape and compressive stresses of the order of −400 MPa in the YSZ layer — is possible by assuming that compressive stresses act not only in the YSZ layer but also in the adjoining surface layer of the steel tape. There are physical reasons for this assumption. Under the ABAD (IBAD) YSZ layer, the tape surface is subjected to a prolonged, intense bombardment by a stream of energetic ions and atoms [2]. As a result of ion-atom hardening [10], the surface layer of the tape can plastically deform (due to the low yield strength of AISI 310S steel, less than 350 MPa [6]) and compress [11]. Incidentally, surface compression of the tape may be one of the reasons for the increased residual stress levels in the YSZ layer noted in [9].

We calculated the stress distribution in the tape as a function of the thickness of the compressed layer (Fig. 5), using the formulas for a film of arbitrary thickness [8]. The „film"was a compressed layer consisting of a YSZ layer and an adjacent steel tape layer (we will call it plastically deformed), which was considered as one because of the similar elastic characteristics of YSZ and AISI 310S. The „substrate" was the remainder of the tape (plastically undeformed). The average stress in it was assumed to be equal to the experimental value $\langle\sigma_{L,T}\rangle = +70$ MPa. The boundary between the „film"and the „substrate"was assumed to be infinitely thin and was not included in the calculations: the plastic strain distribution was described by a step function (a possible real profile of the plastic strain layer is discussed in [11]). The total thickness of the „substrate with the film" was $100\,\mu$m.

As expected, with the increasing thickness of the plastic deformed layer, the effective tensile stress in the tape (the average stress calculated with it in mind) decreases rapidly (Fig. 5, *a*). The compressive stress in the YSZ layer also decreases and crosses the −400 MPa mark at a plastic deformed layer thickness of just over 10% of the tape thickness. The induced tensile stress at the film-substrate interface (Fig. 5, *c*) is approximately +315 MPa and is below the elastic limit of the AISI 310S tape (measured value is 370 ± 20 MPa).

Does the plastically deformed layer affect the position of the diffraction reflections from which the relative strain was determined? To answer this question, we fitted the experimental profile of the diffraction line {113}, assuming that the plastic deformed layer is 15% of the tape thickness (Fig. 5, *b*). Compared to the zero layer, the shift in the center of gravity of the line was 0.005%, less than half the error of determination. Consequently, the plastically deformed layer is practically invisible in the experiment, and using the average value of $\langle\sigma_{L,T}\rangle = +70 \pm 35$ MPa for the main, plastically undeformed part of the tape (Fig. 5, c) can be considered reasonable.

The curvature of the tape caused by the relaxation of compressive stresses increases rapidly with the increasing thickness of the plastic deformed layer (inset in Fig. 5, *a*). At 15% of the tape thickness, it is $0.022\,\mathrm{mm}^{-1}$, which corresponds to a curvature radius of $\rho = 45.5$ mm and a deflection of approximately $1\,\mu$m at a tape width of 4 mm. The calculated radius agrees quite well with the real value, about 50 mm.

Finally, the previously noted increase in the stretching of the tape towards the edges (Fig. 4, *c*) can be explained by the so-called „edge effect" — increased stress concentration near the edges of the „film" [8]. It is beyond the scope of this paper to discuss this effect, as well as the effects at the „film−substrate"interface. A detailed discussion of these issues directly related to tape delamination can be found in [8].

Conclusion

1. The residual stresses in the $100\,\mu$m thick and 4 mm wide AISI 310S stainless steel carrier tape during the YSZ buffer layer application using the ABAD method when manufacturing HTS-2G wire were determined by means of neutron diffraction. The distribution of longitudinal, transverse and normal stresses over the tape width is found.

2. Mechanical polishing has little effect on the distribution of residual stresses. It leads to a slight stretching of the tape in the rolling plane and slightly reduces its initial crescent.

3. The application of the YSZ layer induces a homogeneous isotropic tensile stress of 70 MPa in the tape plane, which visibly smoothens the crescent strain.

4. The model and calculations quantifying the appearance of tensile stresses in the tape after applying the YSZ layer have been considered. It is shown that they arise as a result of relaxation of compressive stresses acting on the surface of the tape in a layer several times the thickness of the YSZ layer. The assumption is made that the compressive stresses on the tape surface are caused by its plastic deformation when applying the YSZ layer.

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Conflict of interest

The authors declare that they have no conflict of interest.

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