Residual stresses in a stainless steel – titanium alloy joint made with the explosive technique

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Abstract. Joining of pipes from stainless steel (SS) and titanium (Ti) alloy still experience serious technical problems. Recently, reliable and hermetic joining of SS and Ti pipes has been achieved with the explosive bonding technique in the Russian Federal Nuclear Center. Such adapters are earmarked for use at the future International Linear Collider. The manufactured SS-Ti adapters have excellent mechanical behavior at room and liquid nitrogen temperatures, during high-pressure tests and thermal cycling. We here report the first neutron diffraction investigation of the residual stresses in a SS-Ti adapter on the POLDI instrument at the SINQ spallation source. The strain scanning across the adapter walls into the SS-SS and SS-Ti pipes sections encompassed measurement of the axial, radial and hoop strain components, which were transformed into residual stresses. The full stress information was successfully determined for the three steel pipes involved in the joint. The residual stresses do not exceed 300 MPa in magnitude. All stress components have tensile values close to the adapter internal surface, whilst they are compressive close to the outer surface. The strong incoherent and weak coherent neutron scattering cross-sections of Ti did not allow for the reliable determination of stresses inside the titanic pipe.

1. Introduction

At the end of 2008 one of the departments of the famous Siemens Company made and published the Siemens global calendar 2009 [1]. Each page of the calendar presents one of twelve outstanding achievements of industries from around the globe in 2008. On the first January page there is an art image of a cryomodule (Fig. 1) constructed at the Fermi National Accelerator Laboratory for the future electron-positron International Linear Collider (ILC). The cryomodule consists of a liquid helium cryostat and a superconducting microwave niobium cavity. One of the elements of this sophisticated structure is the transition element in the form of a two-layer tube (so-called adapter) (see Fig. 1), which connects the cryostat with a two-phase liquid helium supply line running along the entire 35 km length of the ILC.
Figure 1. Art image of the ILC cryomodule.

It was first planned to make the cryostat (as many as about 20,000) and the supply line from titanium. But in this case the cost of the supply line production would be too high. A group of specialists from JINR, which was engaged in the ILC project, proposed that the line be made from stainless steel (SS) and connected with the titanium cryostat through a SS-Ti adapter. Thus, it would be needed to join tightly the dissimilar materials, steel and titanium, which is a serious technical problem. To solve the problem, a group of specialists from the Russian Federal Nuclear Center (Sarov) did the research and development work that resulted in making a batch of SS-Ti adapters by the explosion bonding technique (EBT) [2]. The manufactured adapters have demonstrated excellent mechanical behavior at room and liquid nitrogen temperatures, during high-pressure tests and thermal cycling [3]. The measurements of the residual mechanical intrinsic stresses in the adapter are of large practical interest for the improvement of the EBT and minimization of the production cost. One of the tested adapters was used for the neutron diffraction investigations on the POLDI instrument at the SINQ spallation neutron source (Paul Scherrer Institute, Switzerland).

2. Experiment

The adapter is fabricated from AISI 316L SS and Gr 2 Ti-alloy pipes with the external diameter 59.6 mm and wall thickness 2.3 mm. The adapter joint was established by placing the pipe ends, precisely butted on a tube mandrel, symmetrically inside a loosely fitting external AISI 316L SS cover joint sleeve of wall thickness 2.7 mm. The constituents were welded by external explosion. After that the mandrel was removed from the adapter.

The incident beam was shaped with the sizes of 1.5 x 4 mm$^2$ by the motorized variable vertical and horizontal slits, respectively. The scattered beam at the angle $2\theta$=90° was shaped by the fixed multislit radial collimator with a space resolution of 1.5 mm in the horizontal plane. The strain scanning was performed across the adapter walls in the Ti-SS and SS-SS layers through cross-sections AB and CD symmetrically placed relatively to the butt joint of the SS and Ti pipes (Fig. 2). Three adapter orientations relative to the neutron scattering vector were used to measure the axial, radial and hoop (tangential) strain components. To measure the axial components, the adapter was placed horizontally on the strain scanner while the adapter was oriented vertically with the different azimuthal angles to measure the radial and hoop components.
Figure 2. Sketch of the SS–Ti adapter. The cross-section AB is through the Ti and SS2 layers while the cross-section CD is through the SS1 and SS2 layers.

Note that when the gauge volume (GV) formed by collimators of direct and scattered beams is fully immersed in the sample material, the scattered volume (SV) is equal to GV and the geometric centre of GV coincides with the centre of gravity of SV. In the opposite case they do not coincide. Variation in the position of the SV centre of gravity due to the incomplete filling of GV in material will cause variation in the time-of-flight path length $L$ and the scattering angle $2\theta$ and hence variation in the measured $d$-spacing of the lattice plane $(hkl)$, independent of residual stress. It is the so-called pseudostrain shift of the diffraction $(hkl)$-peak. The evaluation of the pseudostrain effects (in the literature they are sometimes referred to as surface effects) was performed in a few papers, for example, [4-5]. The most trustworthy description of the pseudostrain effects can be obtained by the Monte Carlo simulation. To correct the measured radius $r_{\text{measured}}$ that coincides with the GV geometric centre to the true radius $r_{\text{corrected}}$ that coincides with the SV centre of gravity, we used a model of the one-slit scattered beam set developed for the scattering angle 90° [6]. Of course, it is too rough simplification but it permitted us to describe satisfactorily the experimental data obtained in [4] with a stress-free nickel sample. That is why this model was used to estimate the pseudostrain effects in the described experiment.

As an example, one of the experimental steel spectra obtained in the cross-section CD (the SS1-SS2 layers) is presented in Fig. 3. Note that the strong incoherent and weak coherent neutron scattering cross-sections of Ti did not allow reliable determination of strains inside the titanic pipe due to limitation on the allocated beam time. Each peak of the spectra was fitted individually by the Gauss function. All the steel layers exhibited strong texture different at different measurement points, which affected the peak intensity and, consequently, the accuracy of peak location in the $d$-spacing. After the diffraction spectra analysis only the (311) peak was observed in all spectra, the intensity of which did not vary more than three times.
Omitting the presentation of the $d_{311}$-spacing in all measured points as voluminous we passed to determination of a stress-free value $d_{0,311}$. Two ways were tested using: 1) small coupons from steel materials in the virgin state as delivered before application of EBT (we had in mind that the coupon did not have residual stresses) and 2) requirements of stress and momentum balance conditions and equilibrium relations (BC&ER) [7-9] on the diffraction experimental data. To realize the first way, each coupon was measured three times with its different orientation relative to the neutron scattering vector. The averaged values of $d_{0,311,SS1-coupon}$ and $d_{0,311,SS2-coupon}$ from these measurements were equal to 1.083934(33) and 1.083670(30) Å, respectively. The second way was more complicated. Omitting the BC&ER calculations of $d_{0,311,BC&ER}$ and all admissions that were made during processing the diffraction experimental data for the cross-section CD, we present the result of the calculations as 1.084297 Å. All $d_{0,311}$-values differ from each other. This discrepancy will be discussed during the residual strain and stress calculations below.

3. Strain and stress results

3.1. Cross-section AB (SS sleeve layer)

There are two possibilities of calculating the residual strains in the SS sleeve layer from the experimental data using: 1) the value of $d_{0,311,BC&ER}$ from the BC&ER calculations, and 2) the experimental result $d_{0,311,SS2-coupon}$=1.083670(30) Å obtained with the coupon from as-delivered steel used for the SS sleeve layer fabrication of the SS-Ti adapter. We chose the latter value, the substantiation of which will be done during the residual stress calculation. We omit the results of the strain calculation for lack of place and present the residual stress results in Fig. 4 obtained by using the generalized Hooke’s law.
Here we come back to our promise to substantiate the choice of the experimental value $d_{0,311,SS2-coupon}$ for calculation of the strains and stress. Using the axial stress and momentum balance conditions for the two phase SS-Ti system

$$\int_{r_1}^{r_2} \sigma_a f(r) dr + \int_{r_3}^{r_4} \sigma_a f(r) dr = 0$$

and applying the generalized first theorem of the mean value [10]

$$\int_{r_1}^{r_2} \sigma_a f(r) dr = \mu \int_{r_1}^{r_2} f(r) dr ,$$

where $\mu$ are the stress ($\sigma_a$) or momentum ($\sigma^2_a$) values averaged over the Ti layer, $f(r)$ are $r$ or $r^2$, we can obtain $\sigma_a$ and $\bar{\sigma}_a$ by following equations

$$\sigma_a = -\frac{2}{r_2^2 - r_1^2} \int_{r_1}^{r_2} \sigma_a r dr ,$$

$$\bar{\sigma}_a = -\frac{3}{r_3^2 - r_2^2} \int_{r_2}^{r_3} \sigma_a r^2 dr .$$

Using the experimental data for the axial stresses presented in Fig. 4 and Eqs. (3-4) we calculated that $\sigma_a = 1.04$ MPa, $\bar{\sigma}_a = 6.35$ MPa. The values are very small as we expected from the stress and momentum balance consideration. If we use the value of $d_{0,311,BC&ER}$ all curves in Fig. 4 would be shifted down by about 250 MPa, at that, we will have the values $\sigma_a = 177.2$ MPa, $\bar{\sigma}_a = 176.9$ MPa, which will be in conflict with the stress balance conditions. Thus, it becomes obvious that the value $d_0$ was taken as true for the SS sleeve layer.

3.2. Cross-section CD (SS-SS layers)
In this case, to calculate the residual strains in the SS-SS layers, we used the BC&ER value $d_{0,311,BC&ER} = 1.084297$ Å. The results of the strain calculations were converted in the stresses, which are shown in Fig. 5. Now we can do a back check of the stress balance conditions $\int_{r_3}^{r_4} \sigma_a r dr = 0$ and

$$\int_{r_3}^{r_4} \frac{\sigma_a - \sigma}{r} dr = 0$$

obtained in [9] for a sample of cylindrical symmetry (pipe). The results of...
integration were equal to \(-0.144 \text{ GPa·mm}^2\) and \(-1.286 \text{ MPa}\), respectively, from which the mean values were obtained to be equal to \(-0.03 \text{ GPa·mm}\) and \(-0.26 \text{ MPa/mm}\). The first mean \(-0.03 \text{ GPa·mm}\) must be compared with absolute difference of the means 2.56 and \(-2.69 \text{ GPa·mm}\) obtained for only positive and only negative parts of the integrable function, respectively. The relative difference does not exceed 2%. Thus, the back checking of the balance condition yielded a very satisfactory result. Note that such checking cannot be performed for the cross-section AB because the Ti layer was not investigated.

![Figure 5. Measured (points) and fitted (lines) of the (311) peak residual stresses vs \(r_{corr}\) for the cross-section CD.](image)

4. Equivalent Von Mises stress

Any hard manufacturing process creates a high residual mechanical intrinsic stress field in the material due to its plastic deformation. It was of great practical interest to investigate residual stresses in the Ti-SS adapter from the point of view of their effect on the hermiticity of the adapter at room temperature. The real operating conditions will be even more difficult because the adapters will be used at helium temperatures of 1-2K. In this case, thermostresses will arise from the mismatch of the steel and titanium thermal expansion coefficients.

Usually the thermal stress field in materials is calculated by the finite element method (FEM). The results of FEM are typically presented as the Von Mises equivalent stress

\[
\sigma_e = \sqrt{\frac{1}{2} \left[ \left( \sigma_a - \sigma_r \right)^2 + \left( \sigma_r - \sigma_h \right)^2 + \left( \sigma_h - \sigma_a \right)^2 \right]},
\]

which includes all possible pairwise stress differences \((\sigma_i - \sigma_j)\), where \(\sigma_i\) is the principal stress. Stress is in general a symmetric 3×3 tensor. The Von Mises stress reduces this to a scalar for the purposes of calculating yield criterion known as the maximum distortion energy criterion or the Von Mises criterion \(\sigma_e \leq R_{p0.2}\) where \(R_{p0.2}\) is the yield stress.

The results of the equivalent residual stress calculation in the present experiment are shown in Fig. 6. As is seen in the figure, the equivalent stresses are less than 300 MPa in the cross-section CD, which does not exceed the yield stress \(R_{p0.2}=311 \text{ MPa}\) measured on the as-delivered steel pipe at room temperature but is two times less than \(R_{p0.2}\) in the middle of the SS sleeve layer of the cross-section AB. The stress dramatically increases up to 800 MPa close to the interface between the Ti and SS sleeve layers.
The calculations of the equivalent Von Mises thermal stresses in the most early variant of the adapter [11] showed that thermostresses in the SS and Ti layers amounted to about 420 and 1200 MPa, respectively, during cooling down to 4K. Taking in account last value and the residual stresses the Ti material may be passed deeply into the plastic region that may create a local microcrack. The adapter hermiticity will be under threat during operation. However, the real yield stresses of the adapter materials are unknown. The yield stresses of the materials after the explosion bonding process could probably be lower than in the origin-state materials, which would aggravate the situation. That is why the measurements of the residual stresses in the SS-Ti adapter were crucial for clarifying the situation with the total stresses. A more dramatic situation may be with the SS sleeve layer, where the edge stress effects are very high as a rule.

![Figure 6. Equivalent stresses of (311) peak vs \( r_{\text{corr}} \).](image)

5. Conclusion
Note some important results of the described experiment:

- Neutron diffraction 3D-strain scanning of the SS-Ti adapter and residual stress tensor determination were carried out with the time-of-flight high resolution stress-diffractometer POLDI (PSI).
- The maximal value of all stress components in the cross-section AB through the SS-Ti layers is found to be almost two times larger than the same components in the cross-section CD. In other words, they are very high in comparison with the plastic constants of the austenite stainless steel AISI 316L.
- All the stress components close to the interface between the Ti and SS layers have a tension nature while close to the outer surface they were of a compression nature.
- All the stress components in the cross-section CD through the SS-SS layers close to the adapter intrinsic surface have a tensile nature while close to the outer surface they were of a compression nature. While no stress peculiarity around the interface between the SS-SS layers in the cross-section CD was observed, a rather great rise in the hoop stress component was found near the intrinsic and outer surface of the adapter.
- The radial stress component in the cross-section CD was found to be noticeably smaller than the other components that were observed before in the composite tube from the austenitic stainless steel with the welded ferritic steel cladding [12].
No stress peculiarity was observed around the interface of the SS-SS layers in full contradiction with [12], where a very great rise in the hoop stress component was found in the ferritic steel layer close to the interface between the intrinsic austenitic steel layer and the outer ferritic steel layer.

In general, the residual stresses in the steel part of the adapter did not exceed 1000 MPa, which is a rather large value in comparison with the plastic constants of the austenite stainless steel AISI 316L, such as the yield stress $R_{p0.2} = 170/311$ MPa and the tensile strength $R_m = 485/559$ MPa, where the first value before a slash corresponds to the generally accepted standard requirements on the material and the second value after a slash corresponds to the real tested starting material used to produce the adapter.

The calculations of the equivalent stress in the adapter showed that they were everywhere lower than 800 MPa in the cross-section AB and lower than 200 MPa in the cross-section CD. However, real operation of the adapter at helium temperatures can be accompanied by higher stresses due to summation of the residual and thermal stresses. Thus, it is possible that the total stresses increase up to 2000 MPa in the SS layer of the cross-section AB and up to 620 MPa in the cross-section CD. In this case, the material may pass deeply into the plastic region that might create a local microcrack. The adapter hermeticity will be under threat during operation.

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