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# Assessment of Residual Stresses in ITER CS Helium Inlet Welds Fatigue Tested at Cryogenic Temperature

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**Abstract**. The ITER Central Solenoid (CS) consists of six independent wound modules. The cooling of the cable-in-conduit conductor is assured by a forced flow of supercritical He at 4.5 K supplied by He inlets located at the innermost radius of the coil. The inlets consist of a racetrack-shaped boss welded to the outer conduit wall through a full penetration Tungsten Inert Gas (TIG) weld. They are critical structural elements submitted to severe cyclic stresses due to the electro-magnetic forces acting on the coils. The weld contour is shape-optimised and locally processed by Ultrasonic Shot Peening (USP), conferring large compressive residual stresses on a subsurface layer of several millimetres thickness to improve fatigue strength. The distribution of the residual stresses and the effect of USP on microstructure and mechanical properties is assessed, with reference to the results of a cryogenic fatigue test campaign, performed on peened and as-welded inlets for comparison.

## 1. Introduction

The ITER Central Solenoid (CS) consists of six modules, each featuring 40 pancakes. The cooling of the CS Cable In Conduit Conductors (CICC) using a 45 kA $Nb_3Sn$ conductor is provided by a forced flow of 4.5 K supercritical helium entering through helium inlet nozzles and exiting at outlets [1]. There are 20 inlets per module for a total of 120 inlets [2]. The helium inlets are submitted to severe cyclic stresses over the life of the machine (60,000 fatigue cycles). In order to guarantee hydraulic performance while minimizing stress concentrations the inlets are designed as racetrack-shaped bosses welded to the outer conduit jacket through a 7.2 mm thick, full penetration Tungsten Inert Gas (TIG) weld with an imposed minimum connecting radius of curvature of 6.3 mm (figure 1) in order to guarantee a smooth transition from the boss to the jacket. The material of the jacket and the nozzle is the high-strength austenitic stainless steel JK2LB grade specially developed for the CS conductor jacket featuring a yield strength above 1000 MPa at 4 K and fracture toughness of more than 130 MPa√m following the $Nb_3Sn$ reaction heat treatment (650°C–200 h) [3]. The weld filler is also JK2LB.

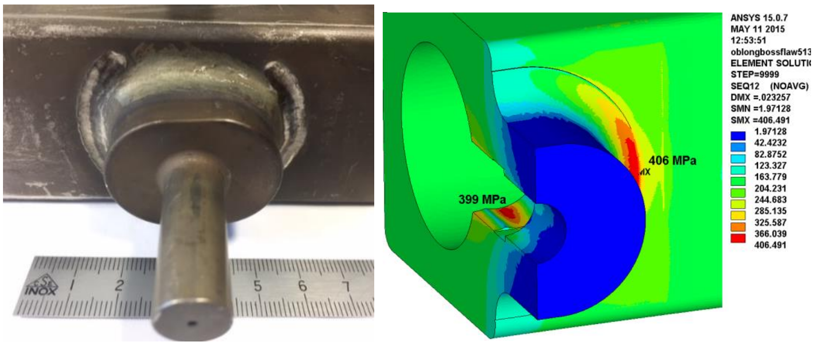


**Figure 1.** Left: view of a CS helium inlet. The contour of the weld between the conductor jacket and the nozzle is shape-optimized and locally processed by USP (metal shining portions). As shown by the finite element model (right), the stresses are the highest at the weld toe around the longitudinal axis. The second region of stress concentration is at the bottom of the internal diameter hole

Fatigue analysis has highlighted that the weld toe of the full penetration weld of the boss is the portion of the weld submitted to the highest stresses (the calculated equivalent stress is around 400 MPa). The weld toe is locally processed by Ultrasonic Shot Peening (USP) in the region of the weld where the stresses are the highest. USP peening is a cold-working surface processing based on ultrasonic waves generated by a sonotrode at frequency of 22 kHz in this specific case. It allows residual weld tensile stresses to be reduced and significant compressive residual stresses to be induced on a subsurface layer under the weld in order to enhance fatigue strength. A Linear Elastic Fracture Mechanics (LEFM) assessment has also shown that beneficial effects of USP to increase the critical size of weld imperfections. In absence of USP, the critical flaw size (in the order of 0.3 $mm^2$) at the inlet weld toe region would be very difficult to identify by Non-Destructive Testing (NDT) techniques. On the other hand, a compressive stress in the weld toe above 200 MPa up to a depth of 1 mm to be imparted by USP would allow to increase the allowable flaw area to 1 $mm^2$ which can be resolved easily by NDT [4].

**Figure 2.** Prototype CS Helium Inlet specimens in the as-received condition for further processing and testing by NHMFL [5]

In order to experimentally confirm the functional viability of the CS helium inlet and the usefulness of USP, a campaign of fatigue acceptance tests has been carried out at 77 K at the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, United States, on six jacket samples each containing two inlets on opposing sides for a total of 12 helium inlets (figure 2). All the six samples were heat treated following welding at 650 °C during 200 h in Ar atmosphere to mimic the reaction heat treatment of the conductor and the welded penetration that applies also to the real CS coils. Following this treatment, on one sample the welds have been left as welded, while on the remaining samples USP has been locally applied to the most stressed portions of the weld toe. The results confirmed that the sample not submitted to USP failed after 158,000 cycles due to initiation and propagation of crack from the weld toe. On the other hand, the USP samples featured much higher fatigue life (between 338,000 and over 850,000 cycles) with crack initiating at the bore of the jacket far from the weld bead and propagating in the parent metal [5]. This proves that USP enabled a change of the failure mode and a substantial improvement of the fatigue performance of the inlets [6]. The present paper summarises the results of the quantification of the residual stresses conferred by USP on the inlet weld toe and its effect on the microstructure and fatigue performance of the inlets.

## 2. Examination methods

Selected welds of the inlet samples have been first non-destructively examined using X–ray Computed Tomography (CT) by a 225 kV Zeiss Metrotom 1500 with a 1024 x 1024 pixel detector, a measuring range of 300 mm diameter times a height of 350 mm and a source-detector distance of 1500 mm. Tests were carried out by Microelectronica S.A. in Romania. Classification of weld imperfections was performed based on ISO 6520-1 and their assessment based on the most stringent level B of ISO 5817. In general, very few weld imperfections were identified. In particular, in one double He inlet peened sample that survived 540,000 cycles shown in figure 3 (sample named "2P"), one weld featured gas pores up to 1.1 mm diameter acceptable to ISO 5817 level B, excess of penetration (within acceptable limits according to the same standard) as well as lack of fusion (not acceptable). The opposite weld featured only acceptable imperfections (gas porosity up to 0.9 mm and tungsten inclusions up to 1.1 mm), as well as an acceptable excess of penetration. No crack initiation arising from weld imperfections was observed in any of the samples. Metallographic examinations of the welds performed in relevant positions following ISO 17639 after grinding, polishing to a mirror – like finishing consistently confirmed the imperfections identified by CT.

Leak tightness tests of the above welds following fatigue testing were also performed by Air Liquide, France with a sensitivity better than $2.0 \cdot 10^{-10}$ mbar·l/s. Both welds were leak tight to a leak rate $< 10^{-9}$ mbar·l/s. Penetrant testing (PT) was also performed according to ASTM E1417 by Level 2 personnel qualified according to ISO 9712. No indications were identified.

Residual stress measurements using the hole-drilling strain-gage method (following ASTM E837) were carried out on the shot peened inlets by Level 3 qualified personnel in strain gauge testing following ISO 9712 by the company SINT Technology S.r.l. in Italy. The measurements have been performed and calculated according to standard ASTM E837 for a non-uniform stress state, based on the assumption that the stresses conferred by USP vary in function of the depth. A CCW - type B strain gage rosette (model 1.5/120R RY61 by HBM /DE) with a diameter of the gage circle of 5.1 mm was installed on the weld toes of the upper and lower inlet with the grid in the axial direction coincident with the longitudinal axis of the weld. An example of equipped workpiece is shown in figure 3. A blind hole of 2 mm diameter with a final depth of 1.2 mm was drilled through the geometric centre of the rosette in 48 acquisition steps, at an advancing speed of 0.10 mm/min between steps. The drilling was executed with a pneumatic turbine at a rotation speed of 25000 rpm in order avoid introducing exogenous stresses. Reading of the strain was performed at each step. The residual stress was calculated from the measured strain values using the non-uniform residual stress field calculation algorithm as per ASTM E837. In this way, the residual stress versus hole depth was obtained from the readings. For the estimation of the residual stresses, measured values of Young's modulus (191.7 GPa [7]), Poisson ratio (0.27 [7]) and yield strength (435 MPa [8]) of JK2LB were used.

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**Figure 3.** Left: workpiece (sample “2P”) equipped with the CCW - type B strain gage rosette; right: test configuration for the measurement of residual stresses based on ASTM E837

Finally, microhardness testing was carried out following ISO 9015-2 (test procedure R, rows of indentations) on a cross sectional cut in the shot peened region of each weld in order to quantify the effect and the extent of the work hardening induced by USP. For comparison, the hardness profile of the unpeened specimen weld was measured in equivalent position for comparison purposes.

## 3. Effects of shot peening

Figures 4 and 5 show the measured profile of the residual stress in function of the thickness for the top and bottom inlet welds, respectively. As expected, the residual stress conferred by USP are compressive and non-uniform in the depth.

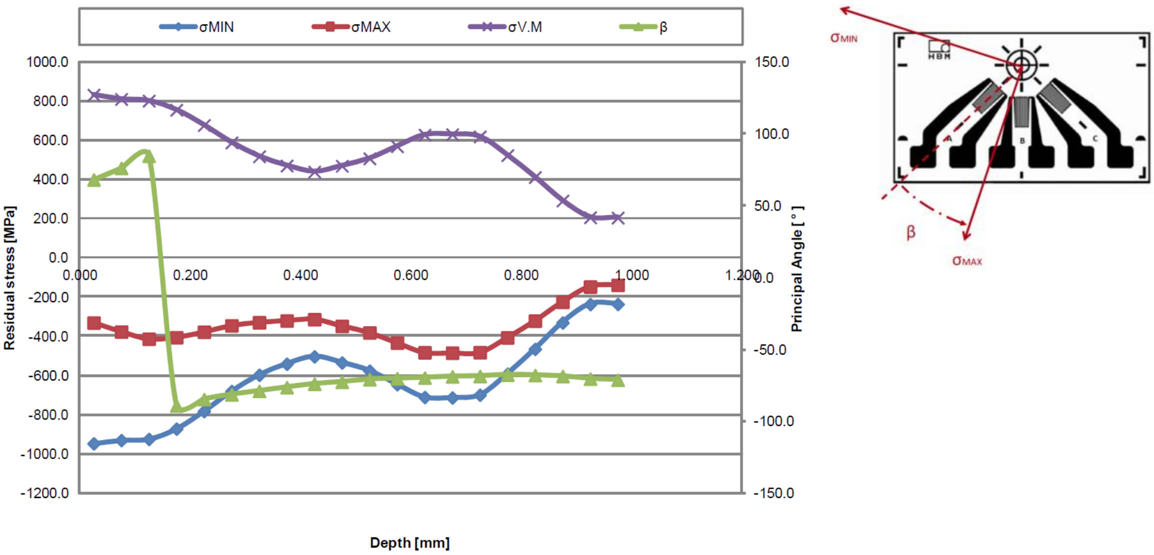



**Figure 4.** Residual stress in function of the thickness for the top inlet weld of sample “2P”. On the x-axis, the depth is measured from the weld toe. $\sigma_{MIN}$ ($\sigma_{MAX}$) is the minimum (maximum) principal stress, $\sigma_{V.M}$ is the equivalent Von Mises stress, β is the principal angle referred (and positioned in the correct quadrant) according to the convention of ASTM E837 (method CCW for rosette type B)

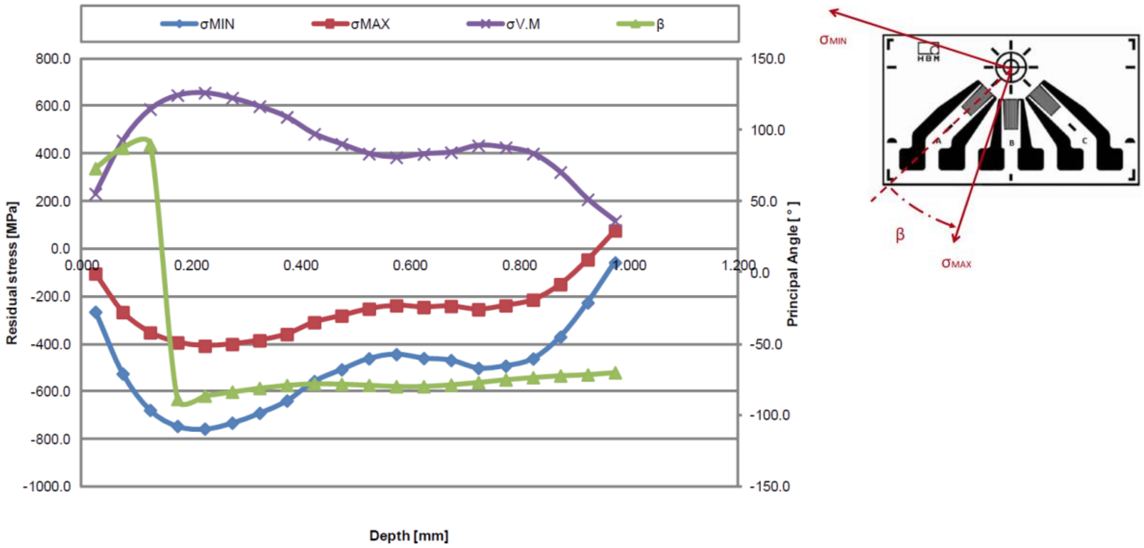
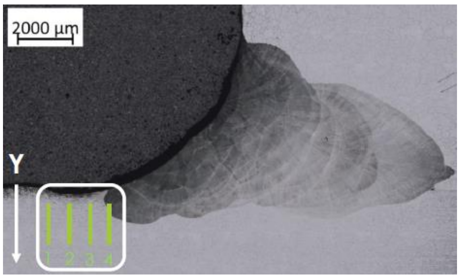



**Figure 5.** Residual stress in function of the thickness for the bottom inlet weld of the same sample




Bottom weld

| Y [mm] | 1 HV0.1 | 2 HV0.1 | 3 HV0.1 | 4 HV0.1 |
|---|---|---|---|---|
| 0.15 | 340 | 336 | 338 | 340 |
| 0.3 | 330 | 326 | 332 | 331 |
| 0.45 | 321 | 318 | 324 | 326 |
| 0.6 | 314 | 309 | 316 | 312 |
| 0.75 | 308 | 301 | 302 | 310 |
| 0.9 | 296 | 294 | 296 | 298 |
| 1.05 | 266 | 271 | 262 | 267 |
| 1.2 | 252 | 250 | 249 | 248 |
| 1.35 | 238 | 236 | 234 | 236 |
| 1.5 | 216 | 218 | 215 | 215 |
| 1.65 | 199 | 206 | 208 | 202 |

Top weld

| Y [mm] | 1 HV0.1 | 2 HV0.1 | 3 HV0.1 | 4 HV0.1 |
|---|---|---|---|---|
| 0.15 | 329 | 331 | 341 | 333 |
| 0.3 | 323 | 326 | 324 | 328 |
| 0.45 | 320 | 316 | 314 | 329 |
| 0.6 | 308 | 306 | 298 | 301 |
| 0.75 | 290 | 289 | 286 | 293 |
| 0.9 | 263 | 261 | 263 | 267 |
| 1.05 | 258 | 259 | 262 | 246 |
| 1.2 | 236 | 242 | 240 | 244 |
| 1.35 | 229 | 231 | 225 | 235 |
| 1.5 | 203 | 212 | 218 | 216 |
| 1.65 | 196 | 198 | 208 | 205 |

**Figure 6.** Results of microhardness testing on shot peened welds. Left, schematic representation of the four microhardness lines measured under the weld toe in a cross cut along the horizontal axis of the conductor. Right: matrix of the measured microhardness values. The vertical distance between indentations along the Y-axis is 150 µm (Y represents the distance from the peened surface), while the distance between two adjacent columns is 1 mm

Residual stresses are measured up to a depth of 1 mm as allowed by the standard. The results are very consistent for the two shot peened welds, both in terms of stress range and principal orientation. For the most of the thickness range explored an equivalent Von Mises compressive residual stress well above 200 MPa is confirmed. To be noted that several stresses significantly exceed 80% of the nominal yield strength (above this limit the stress tends to be overestimated). However, the nominal reference $Rp_{0.2}$ of 435 MPa is in turn underestimated since the material is strongly cold worked by shot peening on a subsurface layer of several millimetres thickness (see below), hence the computed stresses can be considered as representative in the whole measured depth range. Four HV0.1 in – depth profiles along the thickness were also performed starting at the USP weld toe in order to assess the depth affected by the shot peening for the same top and bottom weld in equivalent position, respectively (figure 6). They show an evident hardening induced by plastic deformation down to approximately 1.5 mm. The hardness measured 0.15 mm under the peened surface is up to 341 HV0.1 for the top weld and 340 HV0.1 for the bottom weld. Even at 1.5 mm depth, the hardness is in average above 210 HV0.1, i.e. still above the reference hardness of the unaffected parent metal (192 HV0.1). Results for top and bottom weld are very reproducible. For comparison, the welds of the unpeened samples feature a microhardness of about 200 HV0.1, i.e. very close to the reference value of the parent metal (a slight local increase of hardness is due in this case to the proximity of the weld).

## 4. Discussion and conclusion

In – depth hardness profiles performed under the peened region of the inlet weld toe confirm that the applied USP is able to harden a subsurface layer of 1.5 mm thickness. Residual stress measurements confirm that large compressive residual stresses are conferred down to at least 1 mm under the weld toe in the region where the stress concentration is the highest. The stress is well above 200 MPa down to at least 0.9 mm for one of the welds and down to 1 mm for the other. This compressive stress has a beneficial effect not only by improving fatigue strength, but also by limiting the critical size of weld imperfections in the region of maximum stress and making them easier to identify by NDT. The result of the fatigue test campaign have demonstrated that the residual stresses and hardening conferred by USP are able to substantially extend the fatigue life of the inlets and change their mode of failure. Indeed, failure analysis showed that for the un-peened sample crack initiation occurs as expected in the region of maximum stress of the weld toe, whereas for the peened samples, it is systematically localized in the second high stress region (at the bottom of the jacket hole) [6]. Based on these results, it is confirmed that the peening allowed the initiation to be shifted from the region of highest stress of the weld toe to the region of highest stress of the parent metal.

*The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.*

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