A Comparison of Strains Induced by Manufacturing and Operational Conditions of a Tantalum Clad Tungsten Plate of an ISIS TS1 Solid Target

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Abstract. This paper aims to reveal the relationship between two sets of residual strains. One set of the strains were induced by manufacturing when the Tantalum (Ta) cladding was diffusion bonded to the Tungsten (W) core by Hot Isostatic Pressing (HIP) process. Another set of strains was induced during target operations, i.e., when the HIPED target plates were further bombarded by proton beams for neutron production. The former set was revealed by Neutron Diffraction Measurement (NDM) using the ISIS Engin-X instrument. The latter set was obtained via Finite Element Analysis (FEA) on the ISIS TS1 target assembly. The comparison and superposition of these two sets of strains demonstrated mainly an overall reduction of about 50 micro strains within the Ta cladding. Namely, the strains induced during the TS1 target operation could be beneficial for the specific region of target plate number five (P5) in this case.

1. Introduction

The ISIS TS1 target mainly consists 12 compound Tungsten and Tantalum plates as shown in Figure 1. The tantalum cladding of the target plates is diffusion bonded to the tungsten core by a Hot Isostatic Pressing (HIP) process, during which we believe that residual strains are induced in the HIPED target plate. This is because W and Ta have different thermal expansion coefficients while they were cooled down from 500 °C to room temperature [1]. Neutron Diffraction Measurement (NDM) of the residual strains in a target plate was carried out using the ISIS Engin-X instrument. Residual strain distribution patterns and values within a sample target plate were revealed successfully [1]. This sample target plate of number five is indicated as P5 in red in Figure 1. The selection of this plate was because it is readily available. During the TS1 target operations, however, the target plates are further bombarded by proton beams for neutron productions. Such an operational condition is equivalent to about 100kW of heat load spatially deposited onto the solid target. As a
result, the compound target plates experience elevated temperatures and thermally induced strains and stresses again.

Understanding the relationship between the above two sets of strains is necessary as it could guide the ISIS target safe operation. Namely, if the overall strains within the HIPPED target plate are decreased after the above two set of strains are superposed and compared, that could mean the operational condition is mechanically strengthening the HIPPED target plates. Extra assurance may be provided for operations. On the contrary, if the overall strains superposed within the HIPPED target plate are increased, this could indicate that the operational condition is mechanically weakening the HIPPED target plates. Extra care may need to be taken during operations. To reveal such information quantitatively, we use CFD results obtained previously [2] as input, and a thermal and structural analysis [3] was conducted subsequently. From the recent study, not only the temperature distributions and residual strains within each of the target components and the target assembly were obtained, but also the residual strains within the same area of the same target plate P5 in this case were revealed as planned. These findings may indicate that the strains induced during target operations could be beneficial as overall about 50 micro strains cancellation was produced from the superposition and comparison of the strains for the specific area of the specific target plate in this case. Some of the analysis results will be reported in this paper.

2. **NDM of residual strains induced by manufacturing**

A description of the NDM of residual strains of target plate No. 5 can be found in reference [2]. Details of the sample used in the NDM, including the measurement plane and location are shown in Figure 2 (a). A schematic diagram of the experimental set-up from the top view of the sample in cross section is given in Figure 2 (b), in which the specific measurement area and points are included.

![Figure 2](image_url)

**Figure 2.** NDM of residual strains induced by manufacturing (a) details a quarter of the target plate No.5 and (b) schematic diagram of experiment set-up viewed from the top of the NDM plane

From this NDM, the residual strain distribution patterns induced by manufacturing (the HIPPING process) were revealed quantitatively for the issued area and points as presented in the following **Section 4** for comparison and discussions.

3. **FEA of residual strains induced by operational conditions**

To understand the residual strain distributions induced by operational conditions, an FEA was conducted, using CFD results [2] as input, on the ISIS TS1 target assembly (Figure 1). Owing to its symmetry, only a half of the target was considered in the thermal stress analysis. It also should be pointed out that the FEA used a worst-case scenario in terms of beam history, i.e., it assumed the full beam power of 800MeV, 200µA at 50Hz is constantly hitting the solid target. In addition, to accurately calculate residual stress, three residual strain components are needed, but since the NDM in
In this case only measured two components, corresponding FEA results were therefore post processed and used in this paper.

Some of the typical results are presented in Figure 3 for the residual strains along the FEA X direction. Figure 3 (a) is the strain map within the half target assembly and Figure 3 (b) is the strain distributions within the target plate No. 5. The measurement area indicated with a white square box on the NDM plane in Figure 3 (b) corresponds to the NDM area and points marked in Figure 2 (b) for the residual strains induced by manufacturing. The strains within this area revealed by FEA under operational conditions were further post processed with a view to comparing these two sets of strains.

![Figure 3](image)

**Figure 3.** Residual strains induced by operational conditions along FEA X-direction (a) within half target assembly and (b) within target plate No. 5 along NDM plane and area

It should be noted that similar results for residual strains along the FEA Y direction were also obtained. They are not presented here due to limited space. However, the strain distributions of the FEA Y direction for the issued area and points were post processed in a similar manner to those for the FEA X direction as presented in the following Section 4.

**4. Comparison of strains induced by manufacturing and operational conditions**

From the above investigations, residual strain distributions along the NDM X direction within the specific area of plate No. 5 are shown in Figure 4, where TaVP stands for Tantalum cladding vertical part and TaHP stands for Tantalum cladding horizontal part. A superposition of the X direction strains within the TaHP is presented in Figure 5.

![Figure 4](image)

**Figure 4.** Residual strains distributions along the X-direction revealed (a) by NDM for manufacturing and

![Figure 5](image)

**Figure 5.** Superposition of residual strains along X direction within the Tantalum
As shown in Figure 4 (a), when residual strains induced by manufacturing within the TaVP are mainly compressive, the corresponding ones induced by operation, Figure 4 (b), are mainly tensile, resulting in an overall cancellation of about 50 micro strains. Similarly, while the residual strains within the TaHP are mainly positive (Figure 4 (a)), mainly negative strains caused by operations can be seen within the TaHP in Figure 4 (b). In addition, a superposition of the X direction strains along the bottom line of the TaHP is given in Figure 5, from which a maximum of about 33 micro strain reduction is observed. Also the bottom line of the TaHP in Figure 4 (a) and (b) is the line that is 1mm in from the edge of the horizontal tantalum cladding.

Residual strains along the Y direction induced by manufacturing and by operations are similarly compared in Figure 6 with a superposition of them along the far left line of TaVP given in Figure 7.

As depicted in Figure 6 for the Y direction residual strains, a similar relationship is revealed to those for the X direction ones (Figure 5). For instance, while the strains induced by manufacturing within the TaVP in Figure 6 (a) are mostly positive, mainly opposite sign strains were induced from the operational conditions within the TaVP in Figure 6 (b). This resulted in an overall cancellation of 45 micro strain. A similar reduction of about 32 micro strain was also seen from the superposition shown in Figure 7 along the far left line of the TaVPs in Figure 6 (a) and (b). This far left line within the TaVP is similarly the line that is 1mm in from the vertical edge of the vertical tantalum cladding in this case.

It also should be noted that there is an increase of about 19 micro strains within the TaHPs in Figure 6 for Y direction strains. This increase is however less than the overall maximum strain decrease of about 50 for the X direction and 45 for the Y direction, respectively. We may therefore say that the residual strains induced by operational conditions could be beneficial in this case.

### 5. Conclusions

The relationship between residual strains induced by manufacturing and by operational conditions has been revealed successfully. The latter could be beneficial in terms of mechanically strengthening the ISIS TS1 target as there is an overall strain cancellation within the Tantalum cladding when superposing the two sets of strains. The latter, however, is not beneficial within the Tungsten core as there are mostly strain additions from the same superposition of the two sets of strains. Further investigations of critical areas and critical plates may be needed as the findings from this study may
only be applicable to the sample studied in this case. Topics to explore next should include the correlation between the residual strain with real beam history, accurate residual stress calculation, change of water channel dimensions, and radiation and fatigue damages.

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References
[1] Y. Ma, S. Y. Zhang, D. Jenkins and S. Kabra, “An Experiment of Using Neutron Diffraction to Investigate Residual Strain Distribution in a Hot Isostatic Pressed (HIPPED) Target Plate”, Materials Today: Proceedings 2S, 2015, pp267-273.
[2] Y. Ma, D. M. Jenkins and L. Jones, “A CFD ANALYSIS OF A SOLID TARGET”, NAFEMS World Congress, June 2015, pp. 194-201.
[3] Y. Ma. TS1 Thermal Stress Analysis, January, 2016, ISIS internal report.