Application of X-Ray Diffraction for Residual Stress Analysis on Canadian Naval Platforms

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ABSTRACT

The magnitude and distribution of residual stress fields have a profound effect on mechanical behaviour (ex., fatigue, fracture, degree of distortion) of materials and structures. This is a significant concern for the Canadian Navy, where the superposition of applied stresses on residual stresses may adversely affect the performance, safe operational envelope and service life of naval structures. The ability to elucidate residual stress distribution greatly improves the ability to conduct risk assessments of critical structures. This document illustrates the influence of pressure hull weld repairs on the distribution of residual stress on Canada’s VICTORIA Class Submarines.

The experimental method for calibration of the portable miniature X-ray diffractometer is provided. An X-ray elastic constant of 195 ±6 GPa (for the {211} crystallographic plane of bcc Fe) was experimentally derived for residual stress analysis on submarine QIN steel. The evolution of residual stress during routine pressure hull repairs to Canada’s VICTORIA Class Submarines is discussed, including the recent replacement of the diesel exhaust hull and back-up valves on one of the submarines, as well as a pressure hull plate extraction/insertion/weld procedure on another.

INTRODUCTION

Residual stress is a common occurrence in engineered structures and often arise during each processing step (ex., mechanical forming, heat treatment, joining, fitting) and during maintenance and repair procedures (ex., cold-working, welding, straightening). The magnitude and distribution of residual stress fields have a profound effect on mechanical behaviour (ex., fatigue, fracture, degree of distortion) of materials and structures. This is a significant concern for the Canadian Navy, where the superposition of applied stresses on existing residual stress fields may affect the structural integrity, performance, safe operational envelope and service life of naval structures. The ability to elucidate residual stress distribution would greatly improve the ability to conduct risk assessments of critical structures.

Several studies have been carried out to analyze the residual stress redistribution during modification/replacement of pressure hull plates and penetrations of the VICTORIA Class Submarines. This paper documents the methodology employed to use portable x-ray diffraction
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for the analysis of residual stresses that develop on Q1N pressure hull steel and presents the principal findings from two investigations.

EXPERIMENTAL ANALYSIS METHODS

The pressure hull of the VICTORIA Class submarines is comprised of high strength, high toughness Q1N steel, similar to HY80 steel, that has a minimum yield strength of 550 MPa [1]. The steel pressure hull is coated with a primer layer and an adhesive which is used to attach a layer of acoustic tiles.

The shallow analysis depth of X-ray diffraction (XRD) methods (~ 0.15 mm in steel) required that heavy grease, coatings, paint and/or corrosion layers be removed prior to the analysis. These layers represent physical barriers to the incident X-ray beam and must be carefully removed as to minimize coldwork on the surface of the steel. Coldwork often manifests as macrostrains and microstrains in the near-surface (~ 0.2 mm in steel) that induce residual stresses of up to ± 25 MPa [2]. Electropolishing to ~ 0.2 mm depth has been shown to reduce the presence of stress imparted by mechanical surface preparation processes. This, together with the X-ray penetration depth (~ 0.15 mm), provided residual stress values from the outer-most fibre of the submarine’s shell (within 0.35 mm).

Residual strain measurements were made using a custom portable miniature X-ray diffractometer (mXRD; see Figure 1) developed by Proto Manufacturing Co. Ltd [3]. This system was developed specifically for portable in-situ measurement of strain and quantification of stress in metallic structures. Stress values were quantified by multiplying strain values by a pre-determined X-ray elastic constant (XREC) following elastic theory [1,4]. While methods are available to calculate the XREC using elastic modulus and Poisson’s ratio or to estimate the XREC from literature sources for similar alloys, these methods often introduce significant errors. The spread between these values (both calculated and estimated) could be as high as 20% thus potentially resulting in residual stress errors of similar magnitude [1]. The delicate nature of these investigations required an XREC value with the improved accuracy that is achieved through experimental measurements during bending experiments – in accordance to ASTM E-1426 [4].

Figure 1. The mXRD during four point bend tests for derivation of the experimental XREC (left) and during in-situ measurement on submarine pressure hull (right).
Therefore, four-point bend measurements were conducted in accordance to ASTM E-1426 to ascertain the stress-strain relationship (elastic modulus in bending) and the XREC for Q1N pressure hull steel. For residual stress analysis of Q1N steel, the ferrite phase (specifically the \{211\} planes of the Fe bcc structure) of the steel was used to calculate residual stress values. The XREC (for the \{211\} planes of the Fe bcc structure) was determined to be $195.1 \text{ GPa}$ [1].

**RESIDUAL STRESS ANALYSIS OF SUBMARINE A**

During routine operations, submarine Diesel Exhaust Hull and Back-Up Valve (DEHBUV) materials (Figure 2) may suffer degradation of toughness. This is due to the localized high temperature environment associated with the exhaust gas flow experienced during operation of the submarine. DEHBUVs were often replaced to address this degradation. A residual stress investigation was conducted after replacement of the DEHBUV to:

1. Determine baseline residual stress values to assess the long term stress re-distribution within the DEHBUV and surrounding submarine pressure hull and,

2. Assess the effectiveness of the DEHBUV insertion/welding and heat-treatment procedures.

![Figure 2. Schematic (left) and photograph (right) of the DEHBUV on submarine A.](image)

Prior to this residual stress investigation, the replacement DEHBUVS were fabricated, heat-treated and welded into the pressure hull of Submarine A. Residual stress analysis was conducted at a variety of locations on the exterior surface of the DEHBUVs and the surrounding pressure hull. An example of the resultant residual stress profiles is shown in Figure 3. Residual stress values were determined in the axial direction of the submarine (perpendicular to the weld) on both the aft and forward sides of the DEHBUV. The consistency of values within the DEHBUV casting/plate suggested that the post-fabrication heat treatment had been effective to relax residual stresses. While residual stresses near 0 MPa had been anticipated, the overall shift to compressive values is surprising. Welding the DEHBUV into the pressure hull would likely account for a minor portion of this shift, while a load redistribution in dry-dock may account for the majority of the compressive residual stresses experienced on the DEHBUV.
**Figure 3.** Residual stress profile across the DEHBUV and surrounding pressure hull of Submarine A. Values were determined in the axial direction of the submarine, perpendicular to the aft and forward DEHBUV – pressure hull weld centerline.

High tensile residual stresses on the exterior of the pressure hull over the frames (For Figure 3, this is shown aft of the DEHBUV) showed that the location of structural components have an impact on residual stress values. Although the tensile residual stress were close to the yield stress for Q1N steel, the values may not reflect residual stress values at greater depth. The electropolish depth (~ 0.20 mm), together with the X-ray penetration depth (~ 0.15 mm), provided analysis from the outer-most fibre of the pressure hull steel surface (~ 0.35 mm) only. These regions of high tensile residual stress represented areas for concern as they may be susceptible to crack initiation.

In terms of baseline residual levels, the complex local heating/cooling and resultant inhomogeneous volumetric changes associated with the weld crown and heat affected zone (HAZ) resulted in values that were quite variable. Although the present analysis showed little residual stress variation in the HAZ of welds, the limited spatial resolution of measurement techniques and the high stress gradient makes the HAZ region difficult for use as baseline values. It would be difficult to correlate present and future measurements as slight spatial differences could markedly affect the measured residual stress values. Therefore, only residual stress measurements outside of these areas will be considered as ‘baseline’ values.

**RESIDUAL STRESS ANALYSIS OF SUBMARINE B**

An extraction/insertion/weld repair procedure was conducted to repair a dent in the pressure hull of submarine B. This investigation was conducted to:

1. Quantify the residual stress distribution / redistribution during the weld repair and,

2. Determine baseline residual stress values to assess the long term stress re-distribution within this region of the submarine pressure hull.
During the weld repair, a portion of Q1N pressure hull plate that had been adversely affected by the dent was first removed (Figure 4, left). Then an HY80 plate, with similar mechanical properties and composition to Q1N steel, was fabricated, fit-up and welded into the pressure hull cavity (Figure 4, right).

**Figure 4.** Photographs showing the pressure hull of Submarine B after removal of the affected plate (left) and after insertion/welding of the new insert plate (right).

Prior to this residual stress investigation, the hull plate had been extracted from the pressure hull of Submarine B. Residual stress analysis was conducted at a variety of locations on the exterior surface of the pressure hull in the region affected by the dent repair. One area of interest was near the circumferential berthing weld that originally spanned the dented plate. Figure 5 shows residual stress profiles across the region of the circumferential berthing weld located below the dent repair (see red box in Figure 4). Prior to the dent repair, residual stresses were predominantly compressive with a low tensile residual stress at the toe of the berthing weld. Residual stress profiles before the weld repair were asymmetric and likely a consequence of mechanical constraint associated with the relative proximity of frames. Residual stresses in this region became more tensile after the weld repair. The profiles were also more symmetric after the weld repair. The redistribution of stress was more pronounced in locations near the circumferential berthing weld and over the frame welds.

A portion of the residual stress profiles that contains the weld and HAZ (shaded region) of the circumferential berthing weld is shown in Figure 6. Subsequent to the dent repair, axial stresses in the region were found to be similar to axial and hoop profiles before welding – predominantly compressive with a low tensile stress at the toe of the weld. Hoop stresses were significantly more tensile and had a maximum increase in tensile stress at the weld center.
Figure 5. Residual stress profiles transverse to the circumferential berthing weld and below the dent repair to the pressure hull of Submarine B. Residual stress distribution is shown relative to the weld centerline.

Near the weld toe (Fig. 6), the stress profile was expected to be symmetrical – based on the classical examples in the literature [5]. This was not the case. The asymmetry was likely primarily related to welding of the insert plate (to the pressure hull and frames). Weld shrinkage would be expected to cause increased tensile stress in the hoop direction in the pressure hull plate directly below the weld repair. The observed asymmetry in the circumferential butt weld was likely a consequence of non-uniform strains created during the insert plate welding process.

Figure 6. Residual stress profiles within 60 mm and transverse to the circumferential berthing weld, below the dent repair to the pressure hull of Submarine B. Residual stress distribution is shown relative to the weld centerline and shaded area shows the extent of the weld and HAZ.
Inhomogenous volumetric changes were likely the cause for the residual stress variation in profiles observed over Frames 31 and 32 (Fig 7). Residual stresses at Frame 31 and, to a lesser extent, Frame 32 showed highly variable values. Several locations exhibited stresses near the tensile yield stress that had been experimentally measured on the extracted Q1N pressure hull plate.

Residual stress values were determined in the near-surface region of the steel plate and may not reflect residual stress values within the bulk material. The regions of high tensile stress represented areas for concern as they may be susceptible to crack initiation. It has been envisioned that these highly variable and highly tensile residual stresses may re-equilibrate during the ‘shakedown’ period that is contemporaneous with the submarines initial deep dive. The validity of this statement is expected to be verified following activation of the submarine where the ‘shakedown’ effect will be monitored with strain gages to provide real-time analysis and warning of impending issues.

![Residual stress profiles on frames welded to the pressure of Submarine B](image)

**Figure 7.** Residual stress profiles (left) on frames welded to the pressure of Submarine B (right). Dotted horizontal lines (left) depict the location of upper and lower plate welds.

**DISCUSSION AND CONCLUSIONS**

Accurate depiction of residual stress state in submarine structures using X-ray diffraction requires reliable equipment and methodology for analysis. An experimental XREC of 195 ± 6 GPa was determined for the ferrite phase (specifically, the \(\{211\}\) planes of the Fe bcc structure) for Q1N steel. Experimental derivation of the XREC has been found to more accurately (than literature estimates and estimates from experimental measurement of the elastic modulus) characterize the x-ray elastic properties of Q1N steels.
It is no surprise that maintenance repairs to the pressure hulls of Canada’s VICTORIA Class Submarines have induced residual stresses that modify existing stress fields in the surrounding material. These repairs often give rise to high tensile stresses at weldments and localized variation in stress values – with implications on the structural integrity. This is especially true near welded frames where highly variable and highly tensile residual stresses may develop. Regions of high tensile residual stresses may be susceptible to crack initiation in the future and require monitoring – these have real implications to performance, safe operational limits and service life of the submarines.

These investigations show the influence of plate and penetration (i.e. DEHBUV) weld repairs on the residual stress distribution in submarine pressure hulls. Residual stress analysis has also been used to assess heat-treatment procedures and to provide baseline residual stress values to assess the long term stress re-distribution in submarine pressure hulls. The elucidation of residual stress distribution is important to predicting the performance, safe operational envelope and service life of naval structures.

FUTURE WORK

During October 2009, a comprehensive residual stress survey will be conducted on the pressure hull of one of the submarines to assess the affects of extensive clad repairs on the structural integrity of the pressure hull. This will include residual stress analysis of both the original pressure hull steel (to approximate near-baseline values) and regions of the pressure hull that were repaired by cladding, buttering (overlaying) and/or welding. This will employ the mXRD as well as other residual stress analysis techniques (e.g., ultrasonics, Barkhausen Noise analysis).

REFERENCES


