

Effect of Ultrasonic Peening on Residual Stresses at a T-Butt Weld Toe

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Abstract. The current paper presents the results of neutron diffraction measurements of the through-thickness residual stress field at the toe of a T-butt weld, made from 10mm thick A350 grade black mild steel plates, after successful ultrasonic peening. A single ultrasonic peening treatment was carried out at the weld toe. Residual stresses were measured using the KOWARI instrument at ANSTO. The neutron diffraction technique was chosen for this study because of its ability to measure three-dimensional residual stress deep within the component at high resolutions.

Although the nominal yield stress of the A350 grade plate is 350 MPa the actual yield stress is generally higher, in this case averaging out to about 400 MPa. Ultrasonic peening was highly effective, leading to a residual stress redistribution with a maximum compressive stress of about 250 MPa at the weld toe surface and a maximum tensile stress of 220 MPa, at a depth of almost 3mm into the base plate. The resulting compressive residual stresses at the weld toe surface will almost certainly increase substantially both the fatigue initiation and propagation lives, or may *prevent fatigue completely*. Since A350 steel is widely used in buildings, bridges and offshore structures, ultrasonic peening shows great promise as an in-situ peening method in order to improve weld fatigue performance.

Introduction

A350 grade black mild steel is one of the most widely used structural materials in the world, being commonly found in buildings, bridges and offshore structures. Welding is typically used to join two plates of structural steel and this often takes the form of a T-butt weld. In addition, other more complex geometrical joints are often simplified for stress analysis purposes by approximating them as two-dimensional T-butt plate models (e.g. skewed T-joints, tubular welded joints, pipe-plate joints, etc.). However, all such welds are potentially susceptible to fatigue crack initiation and slow but accelerating growth arising as a result of fluctuating service loads, often eventually resulting in fast fracture.

Ultrasonic peening, more properly known as ultrasonic impact treatment (UIT), is a recent development of the well-established shot peening process. It was originally invented in 1972 in the former USSR to improve the fatigue and corrosion performance of ship and submarine hulls. UIT is similar to conventional needle or hammer peening in many respects. An important difference is that rather than using a pneumatic tool, which causes the needles or a single hammer-like rod to impact



the weld surface at a frequency of 25-100 Hz, with UIT, the weld is impacted by a small number of rods vibrating at a much higher frequency on the order of 18,000-27,000 Hz. This makes it a much quieter device, which vibrates at a lower intensity, so that the operator can use it for longer periods of time before tiring [1]. Ultrasonic peening is relatively cheap, can be applied in-situ and offers significant improvements in the lifespan of welded components when applied correctly. This occurs for three different reasons: removal of weld defects; reduction of stress concentration; and redistribution of tensile stresses and/or introduction of compressive stresses [2].

Experimental Methods

Welding. Dimensions were 800×160×10mm for the base plate and 100×160×10mm for the attachment plate of each T-butt. During fabrication two base plates were tack welded back-to-back prior to welding of the double-beveled attachment plate to each, in order to minimize distortion. Balanced full-penetration GMAW fillet welding was employed, with six passes on each side. All welds passed ultrasonic testing (UT) for internal flaws and magnetic particle inspection (MPI) for surface flaws. Fig. 1 shows the weld detail of a typical T-butt joint before buffing.

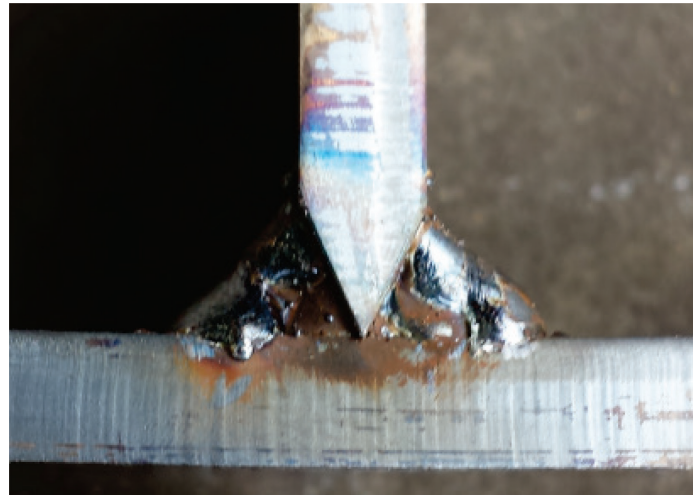


Fig. 1. Weld detail of typical T-butt joint before buffing.

Ultrasonic Peening. Ultrasonic peening treatments were carried out at the base plate and attachment plate weld toes on both sides of one of the T-butts using an Applied Ultrasonics Esonix UIT apparatus. The impact pins were oriented 45° from the treated weld area (perpendicular to the toe line) and the tool was continuously moved in an oscillating motion in a path parallel to the direction of the weld. In order to develop the desired groove, the tool was worked back and forth between a 30° and a 60° angle while maintain the oscillating motion described above. Groove formation was continuously observed during the application process. A properly formed, shiny groove at the weld toe was obtained; this is the main quality assurance inspection point for treatment verification [3].

Neutron Diffraction. It was attempted to measure through-thickness residual stresses from the weld toe into the base plate for both as-welded and ultrasonically peened specimens using the KOWARI instrument at the ANSTO Bragg Institute. The (non-destructive) neutron diffraction technique was chosen for this study because of its ability to measure three-dimensional residual stress deep within the component at high resolutions. For the neutron measurements a 0.5×0.5×1mm³ gauge volume was used for the longitudinal, transverse and normal components. The experimental measurements on the ultrasonically peened sample were successful but those on the as-welded sample were unfortunately shown to be incorrect, as the scan was made slightly inside the weld rather than exactly at the weld toe.

$$\begin{aligned} \text{Weld angle:} & \quad 30^\circ \leq \alpha \leq 60^\circ \\ \text{Crack aspect ratio:} & \quad 0 \leq a/c \leq 1.0 \\ \text{Crack depth:} & \quad 0.01 \leq a/T \leq 1.0 \\ \text{Weld toe radius:} & \quad 0.01 \leq \rho/T \leq 0.066 \\ \text{Attachment width:} & \quad 0.3 \leq L/T \leq 4.0 \end{aligned} \quad (1)$$

Figure 1 consists of three schematic diagrams of a test specimen. (a) Front view: A horizontal rectangular base of thickness T and length L . A vertical rectangular stem of thickness t is attached to the center. The stem has a half-thickness of $t/2$ at its base. The base has a fillet transition with a radius r and an angle α . The distance from the center of the stem to the center of the base is e . (b) Side view: A horizontal rectangular base of length L and thickness T . A vertical rectangular stem of thickness t is attached to the center. The base has a crack of length $2c$ on its top surface. (c) Cross-section view: A horizontal line representing the top surface. Below it is a semi-elliptical crack with a depth a and a half-length c . The total length of the crack is $2c$.

Crack Growth Equations. The Paris Law [8] is commonly used to predict the (Stage 2) fatigue propagation life for a component or structure containing a sharp initial crack. It does not take into

account the influence of mean stress. Another equation which does incorporate the (second order) influence of mean stress on the propagation rate is the Forman Equation [9].

Computer Programs to Predict Fatigue Life. Two FORTRAN computer programs were written to predict the remaining fatigue life for a T-butt welded joint containing a semi-elliptical crack at the weld toe under tension (membrane) loading. The first of these programs uses the BDKH tension parametric equation in conjunction with the Paris Law, and is applicable to a stress-relieved joint. The second program uses the BDKH tension parametric equation together with the HBC tension parametric equation and the Forman Equation, and is applicable to both the as-welded and ultrasonically peened conditions where residual stresses are present.

Experimental Results

Residual Stresses. Although the nominal yield stress of the A350 grade plate is 350 MPa the actual yield stress is generally higher, in this case averaging out to about 400 MPa. Ultrasonic peening was highly effective, leading to a residual stress redistribution with a maximum compressive stress of about 250 MPa at the weld toe surface and a maximum tensile stress of 220 MPa, at a depth of almost 3mm into the base plate (refer to Fig. 3).

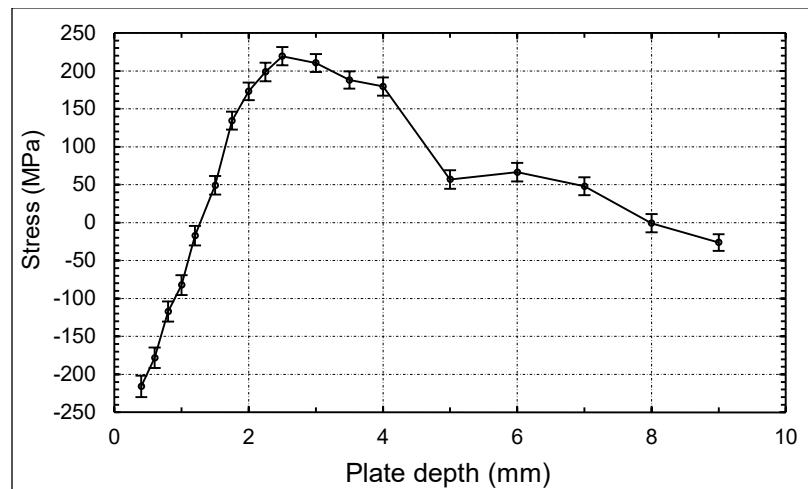


Fig. 3. T-butt weld toe residual stresses through the base plate after ultrasonic peening.

Since there are no measurements in the as-welded state, a typical as-welded residual stress distribution from the literature [10] was used instead, as shown in Fig. 4. The sample investigated using neutron diffraction with a $2 \times 2 \times 2 \text{ mm}^3$ gauge volume was a T-plate fillet weld, joining two 25mm thick plates. The plate material was BS 7191 grade 355 EMZ structural steel, which is very similar to A350 grade steel, and represents a large group of steels commonly used in the nuclear and offshore industries. SMAW welding with standard filler metal was used. Both welds consisted of four weld passes in an alternating sequence between the two sides. For the purpose of this work, the residual stress distribution at the T-butt weld toe centre line was scaled horizontally to fit a 10mm thick base plate.

Geometric, Material and Loading Parameters. Table 1 contains values of the geometric parameters selected for the present analyses.

The fatigue threshold, ΔK_{th} , was taken as $3.2 \text{ MPa}\sqrt{\text{m}}$. The Paris Law crack growth coefficient and exponent were $C = 8.57 \times 10^{-12}$ (SI units) and $m = 3$, respectively. Applied membrane stress varied from 0 to 100 MPa. The number of crack increments employed in the modelling was 10,000.

Preliminary Results. Fig. 5 shows the numerical crack growth results superimposed for: (a) as-welded; (b) stress-relieved; and (c) ultrasonically peened conditions. The analyses conducted assumed that a fatigue crack grows through a static residual stress field. As expected, it is apparent

that the ultrasonically peened T-butt exhibited a longer fatigue life than the stress-relieved specimen, which in turn had a longer fatigue life than the as-welded specimen. It should be noted that the ultrasonically peened specimen had an initial crack depth of 1mm; when it had the same 0.1mm initial crack depth as the other two specimens it exhibited *no fatigue crack growth at all*.

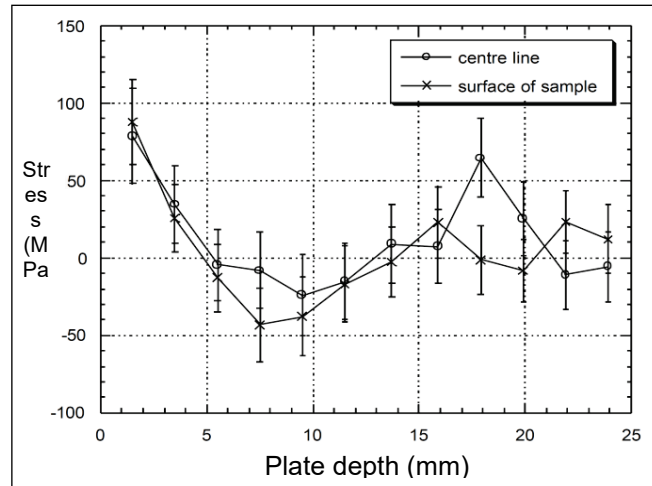


Fig. 4. Through-thickness residual stresses at T-butt weld toe centre line and surface of the sample as a function of base plate depth [10].

Table 1. Geometric parameters of T-butt joints.

Geometric Parameter	Value
Weld angle [α]	45°
Weld toe radius [ρ]	0.1mm
Plate thickness [T]	10mm
Welded attachment width [L]	30mm
Initial semi-elliptical crack depth [a_i]	0.1mm or 1mm
Initial semi-elliptical crack width [$2c_i$]	2mm or 20mm

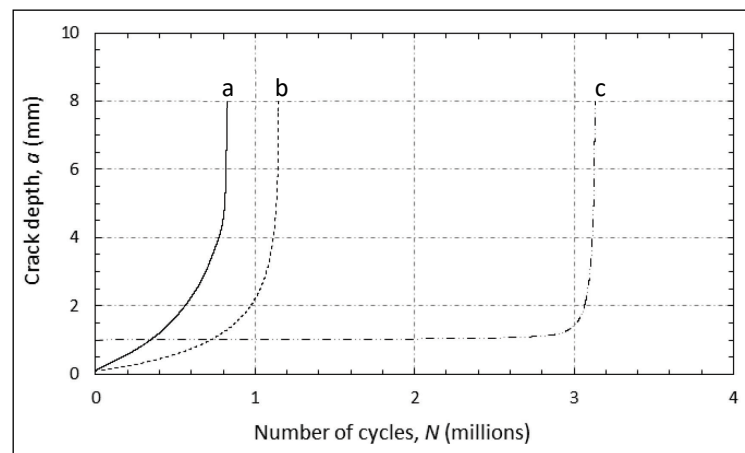


Fig. 5. Fatigue crack growth curves (a) As-welded (b) Stress-relieved (c) Ultrasonically peened specimens.

Conclusions

Ultrasonic peening was found to be very effective at modifying the residual stress distribution. As expected the as-welded residual stresses shortened the fatigue propagation life, whereas ultrasonic peening extended it or *completely prevented fatigue crack growth*.

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