150 Residual Stress Prediction of an Electron Beam Welded P91 Ferritic–Martensitic Steel Plate using the Contour Method

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Abstract

This paper describes the residual stress distribution in electron beam welded P91 ferritic–martensitic steel plate (9 mm thick) using contour measurement method. Ferritic martensitic steels are increasingly used in manufacturing of high integrity structural components such as main steam pipes, boilers and fossil fuelled power generating plants that sustain elevated temperatures [1]. Ferritic martensitic steels containing 9-12 wt. % chromium offer a better high temperature creep resistance than the classical 2.25 Cr-1Mo grades. They are less susceptible to degradation through thermal fatigue due to having a lower coefficient of thermal expansion and higher thermal conductivity compared to stainless steel. However, P91 weldments (made by conventional welding process) in service operation can exhibit premature failure. The failure type falls into the category of 'type IV' cracking due to the position of the cracks. In this case, the weldments will be weakest due to the formation of creep voids in the refined (inter-critical) region of the HAZ of the weld [2], [3]. To improve long term creep properties, the earlier grades of 'type 91' steels are modified through small additions of niobium (Nb), vanadium (V) and nitrogen (N). The modified P91 steels are used together with high energy electron beam welds to enhance the resistance to type IV cracking [4]. High energy density weld (HEDW) processes such as electron beam welding (EB) are capable of providing high penetration into a component. They have a deep, narrow and parallel sided fusion zone in the vicinity of the weld, due to the small thermal contraction in the weld metal compared to conventional welding processes such as arc welding. However, the narrow width of the EB fusion zone introduces a significant high level of residual stresses in the direction of the weld (longitudinal direction) and forms a very fine steep gradient moving away from the weld line within a small region [5], which presents a new challenge for the residual stress measurements. This challenge was addressed in this paper using a promising residual stress measurement technique - the contour method to capture these short length scale residual stresses. This method was invented in 2000 by Mike Prime [3]. It is based on four main steps. The cutting the test component of interest into two halves by wire electro-discharge machining. The cut surfaces deform behind the cutting wire owing to the progressive relaxation of residual stresses. The deformation contours of the two cut surfaces are then measured and used to back calculate a 2-dimensional map of original residual stresses acting normal to the plane of the cut.

In this paper, an EB welded P91 steel plate is selected to measure longitudinal residual stresses (acting in the welding direction) using the contour method. The EB weld causes short length scale residual stresses within the narrow width of the fusion zone with steep stress gradients lateral to the weld line. In order to capture the short length scale residual stresses and improve the spatial resolution of the contour method, the special measures were taken for all main four steps of the technique. For this improved approach, first the specimen cutting was performed with the special care. A thin cutting wire diameter (10 µm rather than standard 25 µm) was used to achieve a better surface roughness, the surface deformation was sampled at a higher frequency, and then, the data analysis steps were performed precisely to measure the short length scale residual stresses, the data smoothed over an optimum length-scale and an appropriate finite element mesh density was chosen. A cross-sectional map of the longitudinal residual stress measured using the improved contour approach is presented in Fig 1. A line profile at 1.5 mm below the top surface of the EB welded P91 plate is shown in Fig 2. The success of the measurement is assessed by comparing the new contour method result to the published first conventional contour measurement result and the neutron diffraction result for the same component [6], [7]. Previously, the initial conventional contour method measurement was unable to resolve the tensile stress peaks in the HAZs adjacent to the weld fusion zone. However, the new contour measurement residual stresses are in good agreement to the neutron diffraction results. It is also shown that the new contour measurement results has been successfully captured the steep stress gradient on both sides of the weld centre-line (0 mm) with tensile stress peaks situated just 2.6 mm apart.

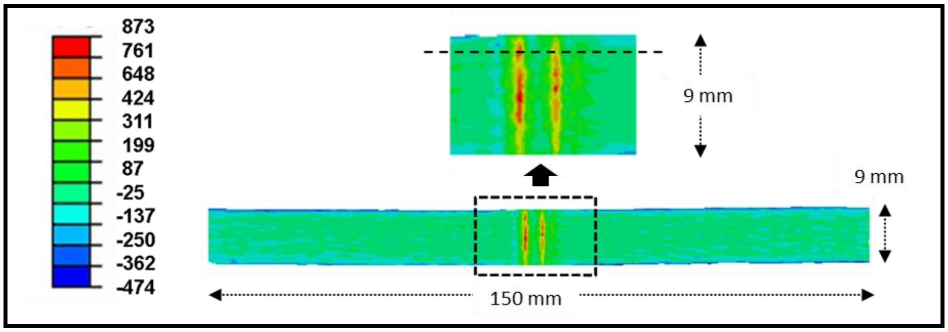

Fig 1: Map of the longitudinal stresses from the improved contour measurements. (Units are in MPa).

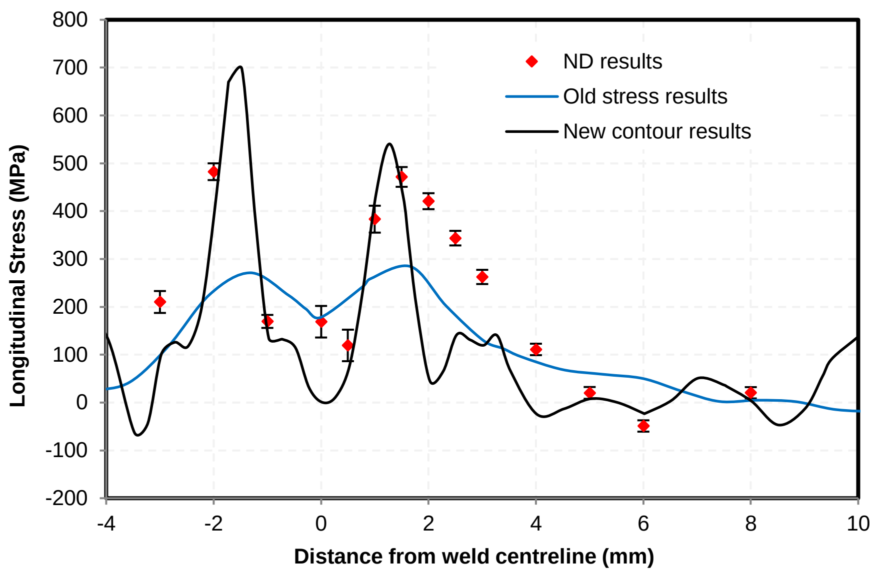

Fig 2: Comparison of the improved and conventional contour measurements with neutron diffraction measurements [6], [7] for a line profile at 1.5 mm below the top surface of the EB welded P91 plate.

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