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# Measured and predicted residual stresses in thick section electron beam welded steels

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ABSTRACT

Four steel thick-section components, created by electron beam (EB) welding, were measured to obtain their residual stress distributions. Two components were made from ferritic steel and two components manufactured from stainless steel. All four components were measured in the as-welded state, with one ferritic steel component then subjected to post-weld heat treatment (PWHT) and measured. Distributions of the principal residual stresses were measured, across the EB welds and through the weld centrelines. Finite element models simulated the welding processes and the predicted residual stresses were compared to the measurements. In the ferritic steel components it was found that the peak residual stresses occur either side of the weld outside of the heat affected zone, with magnitudes corresponding to parent material yield strengths. After PWHT the measured peak stresses reduced from about 600 MPa to 90 MPa. Compressive residual stresses were found at the EB weld entrance and exit positions of the ferritic steel. This was not observed in the stainless steel EB welds, where tensile stresses were measured in the as-welded state. Overall the profiles of the residual stresses predicted by FE analyses replicated the measurements, but the FE analyses always predicted higher peak values. It was found that the measured distribution of residual stresses across the ferritic steel components are very similar irrespective of component thickness and weld speed, with the tensile stresses confined to distances of about 40% of the component thickness. In contrast in a stainless steel component the tensile stresses are much more broadly distributed about the weld centreline.



## 1. Introduction

Electron beam welding (EBW), created in 1950's [1], is a fusion welding method where a beam of high energy electrons is applied to heat the metal weld joint. This process of welding has meant that steel components can be fabricated without recourse to the use of weld filler metals and without prior creation of weld preparation profiles in the parts to be joined. The process has also been demonstrated to provide low distortion particularly for thin sections. In the nuclear energy and aerospace industries, electron beam welding is preferred for manufacturing high-value welds because there is very little distortion of the component [2]. Importantly, the EBW process has to be undertaken in carefully controlled environments and with well-tuned electron beam parameters and is often carried out in a vacuum to prevent dispersion of the electron beam and the reaction between some metals and oxygen. Using a vacuum presents a practical issue for welding large components due to the operational cost and sizes of vacuum chambers available. However, recent developments [3] have led to the creation of a moveable seal and vacuum system. This has opened up the use of EBW on large, practical engineering components [4]. In summary, EBW is a low heat input process, producing a narrow fusion zone and resulting in minimal distortion compared to conventional arc welding processes.

For steel section thickness greater than about 100 mm the volume of welded material is relatively small compared with conventional and narrow gap welding methods. This is illustrated in Fig. 1, where etched cross sections (or macrographs) of a conventional fusion weld is compared with a weld created by an electron beam [4]. However, the creation of small volumes of weld metal

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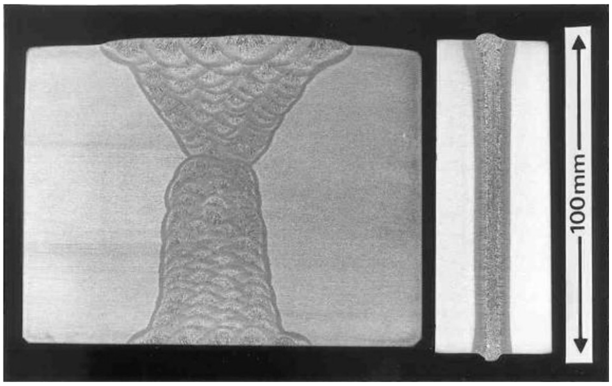


**Fig. 1.** Typical cross-sections through conventional and electron beam welds in steel.

surrounded by bulk parent material also leads to the development of high residual stresses in localised regions. The measurement and prediction of such stresses is extremely challenging for thick section welds and even more so for welds confined to narrow regions through the component thickness.

Earlier work on residual stress measurement of electron beam welds has generally been confined to relatively thin samples. For example, X-ray surface measurements on 2.5 mm thick EB welded steel samples were made by Huang et al. [5]. Although no detail was given about the nature of the electron beam weld, one of the first applications [6] of neutron diffraction (ND) was on a 46 mm thick EB welded steel sample, subsequently cut to smaller section, 10 mm thick, to permit ND strain measurement. Neutron diffraction has continued to be widely used for EB welds created in a variety of metals and their alloys [7–10] but restricted to relatively thin sections, usually between 4 and 14 mm thick. The current limit on depth penetration using the ND method for thick section narrow gap welds (rather than EB welds) appears to be about 50 mm [11]. Thicker sectioned welds, in excess of about 50 mm thick, of the type shown in Fig. 1, appear only to be amenable to a number of mechanical strain relaxation techniques. Evidence of the application of these techniques to thick-section electron beam welded components is, however, limited. Examples include inherent strain [12,13], and deep hole drilling [14–16], although in principle, techniques such as block removal and layering [17], and contour [18], could also be applied.

Predictions of residual stresses resulting from EB welding have also been made and are often done using commercial finite element codes, such as SYSWELD [9,19] and others [12]. The majority of the numerical methods rely on first undertaking a thermal analysis to match experimental temperature measurements and the dimensions of the observed fusion zone. This is followed by a mechanical analysis, together with appropriate (usually time independent) thermo-mechanical properties of the materials. With the exception of the study by Asano et al. [13] there appears to be no evidence of the adequacy or otherwise of FE simulations to predict through thickness residual stress profiles in thick section EB welded components.

The purpose of the present study was to obtain detailed measurements and predictions of residual stresses in thick-section components containing electron beam welds. The thicknesses of the components also suggested that EB welding had created localised and highly triaxial residual stresses. An ideal candidate for measuring the residual stresses would be neutron diffraction. However, in view of the size of the components, neutron diffraction [6,8,11] could not be applied without first reducing the welded components to smaller samples. Furthermore, mechanical strain relaxation methods, such as block removal and surface layering [17,20], are not suited to cases where there are large stress gradients over narrow regions. It was also considered that even the application of the conventional deep hole drilling method (DHD) [21–24] might be problematic because of the presence of steep gradients and high levels of stress triaxiality. Nevertheless, recent work has developed an incremental approach for the DHD method [25]. This permits measurement of residual stresses when plasticity occurs during mechanical relaxation. Alternatively an over-coring approach to the DHD method [26] has been adopted. This method initially relaxes the residual stresses and avoids plasticity during the application of the conventional DHD method. For the purposes of this research all combinations of the DHD method were applied, with parallel and independent work undertaken to predict the residual stresses using the finite element method.

**Table 1**
Summary of components and residual stress measurements.

| Component | Welded state | Measurement location | Notation | Measurement method |
|---|---|---|---|---|
| C1 A553B steel blocks | As-welded | In centre of blocks and perpendicular to and across the EB weld | C1-DHD-1 | Combined standard and incremental DHD, 3 mm reference hole, 10 mm core |
| C2 A508 steel curved sections | As-welded | In centre of curved sections and perpendicular to and across the EB weld | C2-DHD-1 | Combined standard and incremental DHD, 3 mm reference hole, 10 mm core |
| | | EB weld centreline directly through the weld | C2-DHD-2 | Combined standard and incremental DHD, 1.5 mm reference hole, 5 mm core |
| | | 10 mm off-set from EB weld centre -line-notionally in the HAZ | C2-DHD-3 | Combined standard and incremental DHD, 1.5 mm reference hole, 5 mm core |
| | Post weld heat treated | In centre of curved sections and perpendicular to and across the EB weld | C2-DHD-4 | Combined standard DHD, 3 mm reference hole, 10 mm core |
| C3 Stainless steel 316L plates | As-welded | In centre of plate and perpendicular to and across the EB weld | C3-DHD-1 | Combined standard and incremental DHD, 3 mm reference hole, 10 mm core |
| | | EB weld centreline directly through the weld, 300 mm from left-hand edge | C3-DHD-2 | Combined standard and incremental DHD, 1.5 mm reference hole, 5 mm core |
| C4 Stainless steel 304L cylinders | As-welded | Through centre of weld at the 180° location | C4-DHD-1 | Combined standard and incremental DHD, 1.5 mm reference hole, 5 mm core |
| | | Through centre of weld at the 90° location | C4-DHD 2 | Combined overcore and standard DHD, 1.5 mm reference hole, 5 mm core |