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Crack path selection at the interface of wrought and wire + arc additive manufactured Ti–6Al–4V

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ABSTRACT

Crack propagation deviation tendency in specimens containing an interface between wrought alloy substrate and Wire + Arc Additive Manufacture (WAAM) built Ti–6Al–4V is investigated from the viewpoints of microstructure, residual stress and bi-material system. It is found that a crack initiated at the interface tends to grow into the substrate that has equiaxed microstructure and lower resistance to fatigue crack propagation. Experimental observations are interpreted by finite element modelling of the effects of residual stress and mechanical property mismatch between the WAAM and wrought alloy. Residual stresses retained in the compact tension specimens are evaluated based on measured residual stress in the initial WAAM built wall. Cracks perpendicular to the interface kept a straight path owing to the symmetrical residual stress distribution. In this case the tangential stress in bi-material model is also symmetric and has the maximum value at the initial crack plane. In contrast, cracks parallel to the interface are inclined to grow towards the substrate due to the mode II (or sliding mode) stress intensity factor caused by the asymmetric residual stress field. Asymmetric tangential stress in the bi-material model also contributes to the observed crack deviation trend according to the maximum tangential stress criterion.

1. Introduction

Due to their excellent mechanical properties and corrosion resistance, high strength titanium alloys are extensively used as a key structural material in the aerospace industry. At present, titanium parts are mostly fabricated by the conventional wrought based processes such as machining from solid billets and therefore have a very high buy-to-fly ratio [1]. The new additive manufacturing (AM) technology has proved a highly effective method to reduce the production time and cost comparing with the traditional manufacturing process. The Wire + Arc Additive Manufacture (WAAM) process [2,3], which feeds a wire at a controlled rate into an electric or plasma arc to melt the wire onto a substrate or the previously deposited layer, is a developing AM technology that has found applications in the aerospace and other industrial sectors. Compared to the powder-based AM processes, WAAM has a much higher material deposition rate, lower process cost and no powder handling requirement [4]. However a higher amount of post process machining is required due to the lower dimensional accuracy and surface roughness. WAAM is very promising for fabricating large components in high strength titanium alloys.

One of the main challenges to the widespread use of AM technologies to produce safety critical structural components has been widely recognised as the issues of material properties and repeatability [5,6]. So far a number of studies have been conducted in this area for AM Ti–6Al–4V (referred to as Ti-6-4 in the text). These include the static strength, ductility, high cycle fatigue and fracture toughness properties of wire based AM [6–10], powder bed selective laser melting (SLM) [11–14] and powder bed electron beam melting (EBM) [15]. Fatigue crack growth behaviour has also been studied in SLM and EBM Ti-6-4 [11, 14,15]. However, there is no published work yet on fatigue crack growth rates in the wire based AM metals. Furthermore, AM metal may be required to be built on to a substrate in practice; hence the need to study crack growth behaviour at the interface of two different alloys in order to apply the AM alloys in realistic structural assemblies or repairs. Since the damage tolerance design requirement requires not only the fatigue crack growth properties but also modelling and

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predictive tools, it is very important to study the influence of microstructure and residual stress that are identified as the key factors for WAAM built Ti-6-4 [16].

The conventional $\alpha + \beta$ forging processes are widely used to for the high strength Ti-alloy to obtain a typical equiaxed or bi-modal microstructure with excellent mechanical properties [17]. Many studies have been conducted to investigate the microstructure and mechanical properties of AM deposited titanium alloys. Previous studies [3,4] have shown that the β grain of WAAM Ti-6-4 is similar to those in powder bed AM alloys deposited by SLM [18] or EBM [19,20]. The microstructure of WAAM Ti-6-4 consists of fine Widmanstätten α in the upper deposited layers and a banded coarsened Widmanstätten lamella α in the lower layers [9], which is quite different from the equiaxed or bi-modal microstructure of the high strength Ti-6-4 in wrought condition. The coarse lamellar microstructure is also observed for other AM process produced titanium alloys [8,9,20] and is found to retard the crack growth rate [17,21]. The difference in the microstructure results in different mechanical properties. WAAM Ti-6-4 has slightly lower yield and ultimate tensile strengths than those of forged bar, the ductility is comparable but the high cycle fatigue life is significantly higher [9,22]. Furthermore, the as-deposited WAAM Ti-6-4 exhibits direction dependent mechanical properties. In the literature, the welding torch movement direction is defined as the longitudinal direction (L) and the layer building direction is the transverse (T), see Fig. 1. The average yield and ultimate tensile strengths are higher in the longitudinal direction than that in the transverse direction [7]. Fatigue crack growth rate is also slightly greater in the longitudinal than the transverse direction [23]. For the SLM [14] and EBM Ti-6-4 [15], no noticeable difference was observed in the crack growth rate in the Paris law region between the two directions.

Differences in the microstructure and mechanical properties in the wrought and WAAM conditions raise another issue for the designers. WAAM deposited on to a wrought substrate makes a bi-material system with an interface region. Crack path selection and the interface fracture property in bi-material systems have previously been studied [24]. The crack trajectory in a bi-material system depends on the local properties and local stress and strain field. For example, in a laser beam welded aluminum alloy sheet, it is observed that crack extends towards the softer fusion zone that has much lower yield strength than the base metal [25]. The bi-material interface regions are found to be the weakest location for material failure due to the microstructure and mechanical property heterogeneity [26]. Therefore, understanding the crack growth behaviour at the bi-material interface is very important to improve the structural integrity design of WAAM deposited components.

Residual stress caused by the thermal contraction of the melting materials [27] is another key factor that can impact the crack growth behaviour. Residual stress can be either beneficial or detrimental depending on its sign, magnitude, distribution and interaction with the service load induced stress field. Attempts have been made to quantify residual stress in AM parts [27–29]. For example, the neutron diffraction method was used to probe parts produced by the LENS method (a powder based AM process) and found significant compressive residual stress within a built component [28], which were observed to increase the fatigue life as the compressive stress caused crack tip closure; hence retarding the crack growth rate. Another study [29] showed that the peak residual stress shifted as weld beads were added to previous welds and can have the beneficial effect of lowering the peak stress, particularly in the weld toe area, which is a common site of in-service cracking. It should be pointed out that cracking occurs perpendicular to the deposited layers in [28,29]. The influence of residual stress on cracks running parallel to the deposited layers is not found in the open literature.

Experimental tests have been conducted to study the fatigue crack growth behaviour of WAAM deposited Ti-6-4 by our research group [30–32]. A recent paper [33] reported the effects of microstructure and residual stress on the growth behaviour of crack perpendicular to the WAAM–substrate interface. This paper aims to understand the path selection of a crack at the interface either perpendicular or parallel to the interface. Firstly, fatigue crack growth test of compact tension specimens from previous tests is introduced. Subsequently, finite element models are presented for calculating residual stresses retained in the test specimens and resultant stress intensity factors, and investigating the crack path selection in the bi-material system (substrate and WAAM alloys). Finally, crack path selection issues are discussed from the viewpoints of microstructure, residual stress and bi-material system, respectively.

2. Experimental

2.1. Manufacturing process and experimental setup

Fatigue tests of compact tension, C(T), specimens were conducted at Cranfield University [30–32] to investigate crack growth behaviour at the WAAM–substrate interface. The specimens were machined from a "wall" (Fig. 1) fabricated by the Welding Engineering and Laser Processing Centre at Cranfield University using the WAAM technology using process parameters given in Table 1 [30]. A total of four walls were manufactured for this project. One of them was used for residual stress measurement; the other three were used to produce the test specimens shown in Fig. 1. Five C(T) specimens were machined from each wall to fatigue test standard. Fig. 2 shows the geometry and the dimension of the C(T) specimens complying with the ASTM standard [34]. The nominal thickness is 6 mm.

Five different crack scenarios (Fig. 1) were investigated on the fatigue crack growth pattern at the WAAM–substrate interface, which are potentially important for design considerations. Fatigue tests were

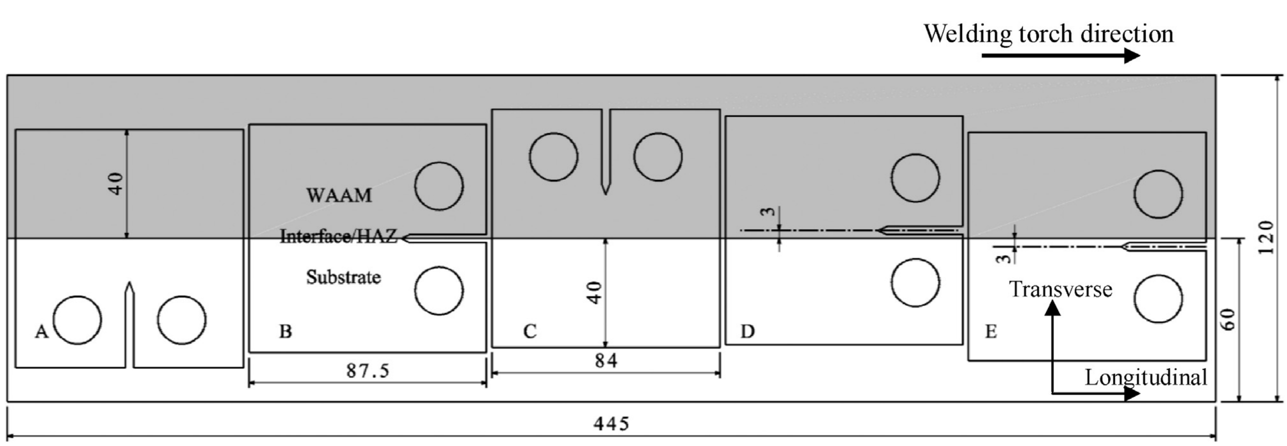

Fig. 1. Layout of test specimens on a WAAM–substrate wall showing the WAAM–substrate interface location on each type of C(T) specimen (unit: mm).