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Keyhole formation and thermal fluid flow-induced porosity during laser fusion welding in titanium alloys: Experimental and modelling

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ABSTRACT

High energy-density beam welding, such as electron beam or laser welding, has found a number of industrial applications for clean, high-integrity welds. The deeply penetrating nature of the joints is enabled by the formation of metal vapour which creates a narrow fusion zone known as a “keyhole”. However the formation of the keyhole and the associated keyhole dynamics, when using a moving laser heat source, requires further research as they are not fully understood. Porosity, which is one of a number of process induced phenomena related to the thermal fluid dynamics, can form during beam welding processes. The presence of porosity within a welded structure, inherited from the fusion welding operation, degrades the mechanical properties of components during service such as fatigue life. In this study, a physics-based model for keyhole welding including heat transfer, fluid flow and interfacial interactions has been used to simulate keyhole and porosity formation during laser welding of Ti-6Al-4V titanium alloy. The modelling suggests that keyhole formation and the time taken to achieve keyhole penetration can be predicted, and it is important to consider the thermal fluid flow at the melting front as this dictates the evolution of the fusion zone. Processing induced porosity is significant when the fusion zone is only partially penetrating through the thickness of the material. The modelling results are compared with high speed camera imaging and measurements of porosity from welded samples using X-ray computed tomography, radiography and optical micrographs. These are used to provide a better understanding of the relationship between process parameters, component microstructure and weld integrity.

1. Introduction

Titanium-based alloys are used extensively in modern aero-engines, to produce a number of critical components, on account of their excellent structural properties particularly when judged on a density-corrected basis. However, such structural components often need high integrity welding methods for their fabrication. Thus, for the joining of complex components, traditional fusion welding techniques still hold considerable importance [1,2], as these processing routes allow for reasonable joint integrity. Fusion welding processes include the older-type arc-welding methods such as TIG, MIG and laser-arc hybrid welding [3–5], and newer beam-welding methods such as laser and electron-beam [6]. The beam processes enable the heat source to become more focused, allowing the molten pool region to form a narrower, deeper weld. These beam-welding applications have a higher power density compared to arc-weld processes. However beam-welding applications such as laser welding are generally good for producing clean, high-integrity weld joints, any fusion welding operation must have associated distortions, and a probability of forming sub-surface defects such as porosity. The size and shape of the weld bead is clearly a critical output for determining weld distortion, and this has been discussed in the literature in the context of validated modelling methods [7].

However, whilst distortions can be relieved with machining or post-weld heat treatments, defects such as porosity remain locked

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within the weld joint once the part has solidified [8]. Porosity defects can occur during the fusion welding processing due to various reasons. Silvinskii et al. [9] hypothesised that the presence of titanium hydride plays a large role in porosity formation. Later, the appearance of pores during the fusion welding of a titanium alloy was attributed to the presence of gas forming substances (oil, grease, moisture) on the surfaces being welded and therefore inadequate cleanliness levels [10]. Weld speed has also been found to correlate with porosity formation [11].

Huang et al. [12] have reported two distinct causes for the formation of defects in an electron beam weld; (i) that the electron beam source becomes fractionally offset from the butt-joint of the 2 parts, thus any remnant gas struggles to escape through the molten pool and in to the weld keyhole, where it can exit the weld entirely. And (ii) the level of hydrogen concentration within the base Ti-6Al-4V material has a considerable impact upon the porosity formation. Hydrogen migration during welding activities has also been studied in an attempt to rationalise the pore formation observed during beam welding applications [13]. Additionally, the morphology and size of the defect formed is believed to give an indication as to its formation mechanism; whereby a round pore of typically 100–300 μm diameter, with a smooth inner surface, would suggest gas-formation (typically hydrogen related) [12,14].

The welding keyhole formed during a high-power density beam welding process is understood to be an unstable phenomenon, with the vapour keyhole shape and interface with the surrounding molten weld pool subject to constant changes as the vapour pressure causes the keyhole to momentarily close up, before re-forming and growing again. Establishing a steady keyhole shape is believed to improve the cleanliness of the weld, reducing the probability of defect formation. The role played by the rapidly changing, undulating interface between the molten weld pool and the vapour keyhole is not well understood, but clearly any liquid/gas interface has a substantial potential for the formation of small gas bubbles or pores within a surrounding different phase.

Computational fluid dynamics (CFD) methods have recently been discussed within the literature [15–20] and applied to beam-welding methods such as laser welding, including the weld phenomena observed in experimental welds such as weld crown and toe formation, defect formation and the keyhole vapour phase present within the weld pool. In this work, we focus on using a validated CFD modelling method to understand better the mechanics occurring at the beginning of welding, during keyhole formation and within the fluid weld pool region, that lead to defect and porosity formation. This is to rationalise the formation of process induced porosity associated with the thermal fluid dynamics. Experimental trials were carried out using bead-on-plate welding as this excludes the possibilities of other sources of porosity from, for example, the surface roughness of two joints or beam offset. It is believed that hydrogen induced porosity will be relatively small due to the low hydrogen content in the alloys [14]. The CFD model is validated using this targeted experimentation and post weld analysis of the fusion zones to determine the presence, location and sizes of pore defects.

2. Experimental and method

2.1. Modelling methodology

The model was constructed and developed using the C++ open source code OpenFOAM® (Open Field Operation And Manipulation) toolbox, and uses a single material (metal) with multiple phases (solid, liquid and gas). It uses the standard balance of forces and conservation of momentum and energy; it also includes reaction forces from vaporisation, and Marangoni force, and the laser is applied as a volumetric heat source. It does not include momentum coupling between the vapour phase and other phases however. The model assumes that the Reynolds number of the molten liquid metal within the weld bead is sufficiently low such that a laminar solver is appropriate. Similar assumptions are made in other CFD modelling approaches for fusion welding [19–22]. The choice of representation of the laser interaction with the material is significant. A full optical model would be ideal, using the complex material refractive index and including interaction with the plasma. However the computational requirements are extreme [20] and there are unknowns concerning the plasma properties. An engineering approximation (e.g. Ref. [23]) is to represent the multiple reflections by a volumetric energy density. This pre-supposes some aspects of the nature of the solution, but is capable of being predictive over the range of cases presented in this paper. A brief summary of the theoretical framework used in simulating the weld pool dynamics during fusion welding has been given here. A detailed description of the approach is outlined by Panwisawas et al. [21]. The starting point is the usual assumption of material is incompressible expressed in terms of the continuity condition,

$$\nabla\cdot\boldsymbol{u} = 0 \tag{1}$$

where, $\boldsymbol{u}$ is flow velocity. The computation domain is divided into a metallic α_1 region and atmospheric gaseous α_2 regions. The solid, liquid and vapour metal constitutive behaviours are defined within α_1 by introducing appropriate phase transformations depending on the temperature, being either below the solidus, between the solidus and liquidus temperature, above the liquidus temperature or above the vaporisation temperature. Above the vaporisation temperature, metal liquid transforms to metal vapour. The latter vapour phase is converted in to α_2. The summation of metallic α_1 and gaseous phases α_2 is always unity, i.e. $\alpha_1 + \alpha_2 = 1$, in every fluid element. Additionally, a weight function of any parameter x is used to smear out the effect of metallic and gaseous phases, defined as, $\bar{x} = x_1\alpha_1 + x_2\alpha_2$. Modelling the dynamics of the weld pool is achieved by tracking the evolution of the α_1 and α_2 phases by a continuity condition with appropriate source/sink terms corresponding to phase transitions.

Thus, the volume occupied by the α_1 phase will evolve through the following differential equation,

$$\frac{\partial\alpha_1}{\partial t} + \nabla\cdot(\alpha_1\boldsymbol{u}) = -\frac{\dot{m}_V}{\rho_2} \tag{2}$$

where t is time, and the sink term in the right hand side (RHS) describes the loss of metallic phase due to evaporation when the evaporation temperature T_V is reached. In this work, ρ_2 is referred to the density of metal vapour which is no difference from atmospheric gas phase as chemical species is not distinguished here. The mass evaporation rate $\dot{m}_V$ is a function of the vapour recoil pressure p_V [17,20,25,26]. As reported previously in Refs. [27,28], the beginning of interaction between heat source and the materials predicts the kinetics of the melt pool. The governing field equation describing the flows of the liquid metal in weld pool and metal vapour is the Navier-Stokes equation,

$$\frac{\partial\bar{\rho}\boldsymbol{u}}{\partial t} + \nabla\cdot(\bar{\rho}\boldsymbol{u}\otimes\boldsymbol{u}) = -\nabla p + \nabla\cdot\boldsymbol{T} + \boldsymbol{f}_{bouyancy} + \boldsymbol{f}_{melting} + \boldsymbol{f}_{surface} \tag{3}$$

where $\boldsymbol{T}$ is the viscous deviatoric stress tensor, p the hydrostatic pressure, and $\bar{\rho}$ is the density. Appearing on the right hand side of Equation (3) is a number of force terms. The buoyancy force term $\boldsymbol{f}_{bouyancy}$ is caused by density differences due to thermal expansion.