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A computationally efficient thermal modelling approach of the linear friction welding process

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ABSTRACT

Numerical models used to simulate LFW rely on the modelling of the oscillations to generate heat. As a consequence, simulations are time consuming, making analysis of 3D geometries difficult. To address this, a model was developed of a Ti–6Al–4V LFW that applied the weld heat at the interface and ignored the material deformation and expulsion which was captured by sequentially removing row of elements. The model captured the experimental trends and showed that the maximum interface temperature was achieved when a burn-off rate of between 2 and 3 mm/s occurred. Moreover, the models showed that the interface temperature is reduced when a weld is produced with a higher pressure and when the workpieces are oscillated along the shorter of the two interface dimensions. This modelling approach provides a computationally efficient foundation for subsequent residual stress modelling, which is of interest to end users of the process.

1. Introduction

Linear friction welding is a solid-state joining process involving a stationary workpiece rubbed against another with a linear motion, under a compressive force to generate heat by friction and plastic deformation. The large deformation undergone by the material during the process usually results in a refined microstructure which can improve the properties of the weld relative to the parent material. Li et al. (2012) found an increase in the tensile strength at the joint when appropriate welding parameters are used. Wanjara and Jahazi (2005) recorded the highest hardness values at the weld centre for all the welding conditions considered. Wang et al. (2017) found evidence of anisotropic mechanical properties within titanium LFW due to the strong texture developed. Typically, less than 10 s are required to complete a titanium alloy weld using LFW, making it a fast welding process which also offers good repeatability. As detailed by Kumar (2013), LFW has been successfully implemented to weld titanium and nickel-based super alloy bladed-disks.

LFW was first divided into four phases by Vairis and Frost (1998) with the initial, transition, equilibrium and forging phases. During the initial phase, heat is generated by friction of the asperities located at the interfaces of the workpieces until the temperature is sufficient to create a viscoplastic layer, characteristic of the transition phase. At this point, the viscous material starts to be expelled from the interface creating flash. Most of the flash occurs during the equilibrium phase, where a quasi-steady state is reached for the interface force, thermal profile and burn-off rate. Once the desired upset is achieved, the two parts are quickly and accurately aligned and a forging force is applied to consolidate the joint.

Owing to the rapid nature of LFW, it is difficult to get an insight into the process and as explained by Li et al. (2016) the choice of welding parameters have a significant impact on the heat generation and material flow. Therefore, many authors have used numerical modelling as an alternative to gain fundamental knowledge about LFW. Li et al. (2010) developed a 2D fully-coupled model which predicted a temperature of 1000 °C within 1 s of welding. However, no thermocouples recording were provided to validate the numerical predictions. Schroeder et al. (2012) demonstrated the dependency of the flash morphology upon the process parameters used, experiments and models exhibited a good match. McAndrew et al. (2015a, 2015b) used numerical models to evaluate the surface contaminant removal. A high applied pressure was recommended to minimise the amount of burn-off necessary to expel the contaminants. Numerical predictions were compared with metallographic images to observe the contaminant evolution. Turner et al. (2012) replicated numerically the welding conditions investigated by Romero et al. (2009) who conducted synchrotron X-ray diffraction experiments to predict the residual stress within LFW. Due to the lack of experimental data at the weld interface, it is unclear if peaks of residual stress are correctly predicted. Authors in the literature have attempted to model the complex mechanical mixing of LFW at the weld interface between the two parts. Unlike most other friction welding process, models of LFW in the literature are mostly fully-coupled. For example, Grant et al. (2009) developed a sequentially-coupled model simulating inertia friction welding where the

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rotational motion of the process was not modelled. Thermal and mechanical predictions were found in a good agreement against experiments.

Three flow modelling approaches have been applied to LFW in the literature. The first approach developed by Vairis and Frost (2000) used a deformable body oscillated against a rigid body. Computational time was reduced with this approach; however a temperature dependant friction coefficient needs to be defined to account for the heat generation. Furthermore, the mechanical mixing occurring at the interface to form the joint cannot be modelled since only one body is deformed. Similar to the first approach, the second involves two deformable bodies rubbed against each other. Despite the use of two deformable bodies, the mechanical mixing is still not representative of the real process since the two interfaces do not merge. Turner et al. (2011) solved the problem by using a single body to represent the two original parts, and a thermal profile accounting for the heat input from the initial phases was mapped onto the mesh, allowing the material at the centre to deform. Using this approach McAndrew et al. (2015a, 2015b) successfully modelled the flash morphology for several welding conditions.

There are two dominant approaches to account for the heat generated during the welding phases within a numerical model. The first method uses a temperature dependant friction coefficient with a fully-coupled model to generate the heat during all the welding phases. Blau (2001) stated that the number or factors which potentially influence the friction coefficient is large and includes: contact geometry, fluid and flow properties, relative motion, applied forces, temperature and stiffness and vibrations. As a consequence, it is necessary to apply extra care when using friction coefficient values. The second method was first used by McAndrew et al. (2014) where the machine data recorded during welding were post-processed to determine the average heat flux over the initial phase. This was applied to a thermal model to predict the temperature distribution. After this, the single-body method mentioned above (developed by Turner et al. (2011)) was used to model the equilibrium phase, and an inelastic heat fraction was specified, typically in the range of 90–100% to represent the amount of mechanical work converted to heat. Both these approaches modelled the oscillations, so 3D models are computationally expensive and require weeks to complete a simulation as mentioned by McAndrew et al. (2016). Therefore, models are often limited to two dimensions and complex geometries cannot be considered.

The primary purpose of this paper is to present a novel modelling approach, experimentally verified, able to predict the temperature history of a linear friction weld that bypasses the modelling of the oscillations. Effects of rubbing velocity, burn-off rate, applied force and oscillation direction on the temperature histories are investigated.

2. Methodology

2.1. Experiments

Ti–6Al–4V linear friction welds were made at TWI Cambridge using the Thompson E20 machine for the five welding parameters listed in Table 1. As shown in Table 1, some of the welding parameters were replicated to account for experimental variability. These welding parameters cover most of the operating window of frequency, amplitude and applied force of the LFW machine used. The experiments used workpieces measuring 20 × 40 × 60 mm, which is illustrated in Fig. 1. The Ti–6Al–4V parent material had a bimodal alpha-beta microstructure. Experimentally the workpiece was oscillated in the x direction (along the interface dimension 40 mm), except for weld 5 where it was oscillated transverse to this. Thermal histories were recorded during the welding process using k-type thermocouples with an outer diameter of 1 mm. EDM was used to produce the 1.2 mm diameter holes shown Fig. 2(a). The thermocouples were inserted at depths of 0.3 mm, 1.2 mm, 2.7 mm, 4.2 mm and 5.2 mm from the weld interface and an epoxy resin was used to fix them in place. To get the thermocouple wires out of the clamping tool, a groove was machined on one workpiece, as shown in Fig. 2(b).

Table 1
Welding parameters.

Weld	Freq. (Hz)	Amp. (mm)	Applied pressure (MPa)	Burn-off (mm)	Rubbing velocity (mm/s)	Oscillation direction along the interface dimension:
1	20	1.5	90	3	120	40 mm
2;6	30	2	90	3	240	40 mm
3	50	2.7	40	3	540	40 mm
4;7;8	50	2.7	90	3	540	40 mm
5	50	2.7	90	3	540	20 mm

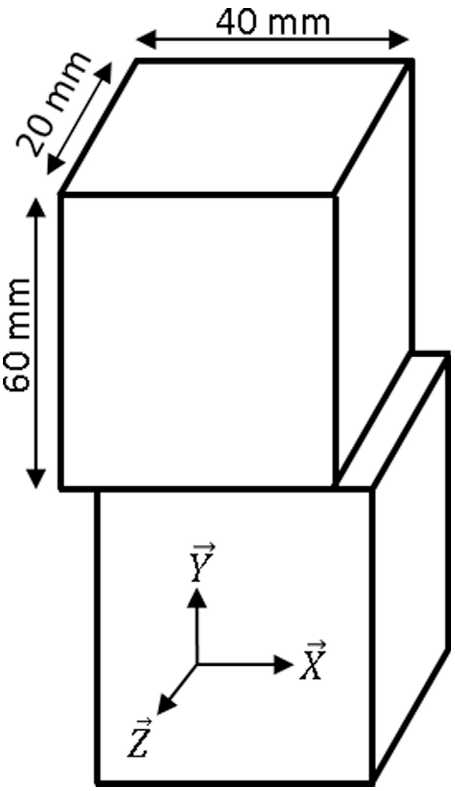

Fig. 1. Workpiece dimensions and axis.

The influence of the rubbing velocity was studied in the results section by comparing welds 1, 2 and 4. The average rubbing velocity, first defined by Addison (2008), is determined from the frequency f and amplitude A with $v_r = 4Af$. The effect of the applied force is examined using welds 3 and 4, while the oscillation direction is studied using welds 4 and 5.

During linear friction welding, several parameters were monitored with high-speed data acquisition systems including the oscillator position x, the in-plane force F_i, the axial position representing the burn-off and the applied force F_a applied on the non-oscillating workpiece, as shown in Fig. 3.

A similar approach to that developed by Ofem et al. (2010) and reemployed by McAndrew et al. (2015a, 2015b) was used for analysing the machine data. The machine data obtained during welding was post-processed and the average heat flux (Watt) per phase was calculated with the following formula:

$$\dot{Q}_{Phase} = \frac{\int_0^{T_{Phase}} F_{\text{int}} v dt}{T_{Phase}}$$