Numerical modeling of linear friction welding: a literature review [*]

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Abstract *Linear friction welding (LFW) is a solid state process for joining metals together. While this process was developed originally for titanium alloys (e. g. blisks), over the past decade a number of materials were found to be weldable with LFW. In this review, the current status of understanding and development of LFW are presented. Particular emphasis has been given to the modeling of the LFW process. Finally, opportunities for further research and development of LFW are identified.*

Key words linear friction welding, finite element modeling, process optimization

0 Introduction

Friction welding (FW) is a group of joining technologies sharing the common characteristic of using friction as the means to generate local heat, with the rotary friction welding (RFW) being the most popular variant of those. In this group, linear friction welding (LFW) and friction stir welding (FSW) are relatively new solid state bonding processes aiming at extending the current applications of RFW to non-axisymmetric components. There are many publications on numerical modeling of FSW[1-2] and RFW[3-4].

As for LFW, there are approximately 73 publications indexed by SCI on the process from 1992 to 2013, while there are many non-English publications, in other languages such as Chinese and Russian which are not included in that list. The majority of these papers are on LFW of titanium alloys, fewer on nickel-based superalloys, and very few on steels, MMCs and dissimilar metal combinations. However, there is no comprehensive review on the process with only available brief reviews by Nunn[5] and Bhamji et al[6].

Experimental observations can be of limited use in LFW due to non-linear effects in a narrow weld zone, such as the variation of thermo-physical properties with temperature and the change of mechanical properties with deformation conditions (temperature and strain rate). The very complex thermo-mechanical coupling during LFW makes it difficult to reveal the bonding nature and predict various properties of the joints. Numerical analysis using advanced computational tools can play an indispensable role in providing insight into this complex LFW process. Therefore, this review will summarize in detail the numerical modeling of LFW.

1 Heat generation rate

LFW joins metals together through intimate contact of a plasticised interface, which is generated by frictional heat produced as one component is moved under pressure in a direct reciprocating mode relative to another. This process has four distinct phases, which include the initial phase (ph. I), transition phase (ph. II), equilibrium phase (ph. III) and deceleration (or forging) phase (ph. VI). There are several key parameters during LFW[6-7] (Fig. 1), which have significant impact on joint proper-

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ties. These are oscillation frequency, oscillation amplitude, friction pressure, forging pressure, friction time, forging time, and the resultant welding time, axial shortening and burn-off rate. In practice, axial shortening has been usually used as control feedback for a successful joint.

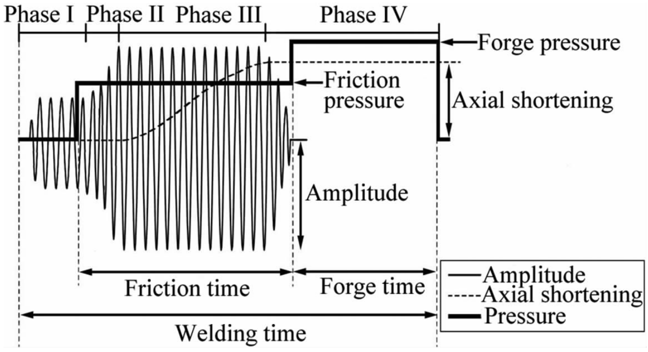

Fig. 1 Process parameter changes during a typical LFW run[6]

A limited number of papers have been presented on the mathematical modeling of the LFW process[8-9]. A heat input model for the equilibrium phase of the process has been developed, where the heat generation rate per cycle per unit interfacial area (q) is:

$$q = \tau v = \frac{F_S}{A} v = \frac{\mu F_N}{D(W - \alpha \sin(\omega t))} \alpha \omega \cos(\omega t) \tag{1}$$

where τ is the shear stress, v is the sliding velocity, μ is the coefficient of friction, F_S is the shear force, F_N is the normal force, α is the amplitude of oscillation, ω is the angular frequency ($\omega = 2\pi f$), t is the welding time, D is the thickness and W is the width of the specimen (weld area $= DW$)[6]. The contact area term $D[W - \alpha \sin(\omega t)]$ changes with time to reflect the true area of contact[6].

The average heat generation rate is used to estimate the effect of process parameters. It can be written as:

$$q = \frac{1}{T}\int_0^T q_0 \mathrm{d}t = \frac{4}{T}\int_0^{T/4} q_0 \mathrm{d}t = \frac{4}{T}\int_0^{T/4} \mu P_N v \mathrm{d}t = \frac{4}{T}\int_0^{T/4} \mu P_N \alpha \omega \cos(\omega t) \mathrm{d}t = \frac{2}{\pi} \mu P_N \alpha \omega \tag{2}$$

where q_0 is the heat generation rate per cycle per unit interfacial area, P_N is the constant friction pressure, t is the welding time, T is the oscillation cycle period[10].

It can be seen from Eq. (2) that q is proportional to friction pressure, as well as to the amplitude and frequency of oscillation. If the amplitude of oscillation were to be reduced, the frequency would necessarily need to increase proportionally for the same axial load conditions to produce welds without taking into consideration any strain-rate hardening effects on the material properties[11]. The heat generation rate required to produce sound welds increases with increasing frequency of oscillation for the same amplitude of oscillation and friction pressure for strain hardening materials[11]. According to Wanjara and Jahazi[12], there is a critical power input (PI) at approximately 2.4 kW, above which sound Ti64 joints can be manufactured without any welding defects.

In addition, according to findings from FSW[13], the interfacial heat could be derived from the shear stress of material under a sticking friction condition, as described by the von Mises yielding stress:

$$\tau_s = \frac{\sigma_s}{\sqrt{3}} = 0.577 \cdot \sigma_s \tag{3}$$

Therefore, Eq. (2) can be rewritten as:

$$q = \frac{2\sigma_s \alpha \omega}{\sqrt{3}\pi} = \frac{4\sigma_s \alpha f}{\sqrt{3}} \tag{4}$$

If one takes the initial sliding friction into account, the interface heat input will depend at the beginning on the normal pressure and then on the temperature-dependent flow stress when the interface temperature is high enough for yielding to occur, which can be expressed mathematically as:

$$q = \begin{cases} \dfrac{4P_N \alpha f}{\sqrt{3}} & T \leqslant T_s \\ \dfrac{4\sigma_s \alpha f}{\sqrt{3}} & T > T_s \end{cases} \tag{5}$$

If the interface heat power is assumed to be constant, the temperature history can be estimated:

$$T(x,t) - T_0 = \frac{2q\sqrt{\frac{at}{\pi}}}{\lambda}\exp\left(-\frac{x^2}{4at}\right) - \frac{qx}{\lambda}erfc\left(\frac{x}{2\sqrt{at}}\right) \tag{6}$$

where $erf\left(\frac{x}{2\sqrt{at}}\right)$ is the error function, $erfc\left(\frac{x}{2\sqrt{at}}\right) = 1 - erf\left(\frac{x}{2\sqrt{at}}\right)$, T_0 is the initial temperature and a is the thermal diffusivity defined as $a = \frac{\lambda}{\rho c_p}$. At ph. III, where steady state material extrusion occurs the interface temperature will have a steady value less than the melting temperature of the material to be welded, and the axial shortening rate (or burn-off rate) will be constant. By introducing the axial shortening rate into an 1D unsteady heat conduction equation, it can be written as:

$$\kappa\frac{d^2T}{dx^2} - v\frac{dT}{dx} = 0 \tag{7}$$

where thermal diffusivity $\kappa = \lambda/(\rho c)$, λ, c and ρ are thermal conductivity, heat capacity and density, respectively, v is the shortening speed. Therefore, the temperature distribution from the interface to the cold end will be almost steady with time. As given by Wen et al.[9], the temperature is described as:

$$T = K_1\frac{\kappa}{v}\exp\left(\frac{v}{\kappa}x\right) + K_2 \tag{8}$$

Wen et al.[9] measured the temperatures at two positions in the workpiece to estimate the constants K_1 and K_2, and estimated the interface temperature at $x = 0$.

2 Finite element modeling of LFW

With the development of computer technology and numerical analysis theory, the finite element method (FEM) has become a powerful and reliable technique for the prediction of temperature and stress fields in the parts. It can provide insight into the complex LFW process. In addition to the use of mathematical modeling, 2D or 3D thermo-mechanically coupled models have been used in the finite element analysis (FEA). During such an analysis heat input at the interface is the most important factor.

2.1 Main works in LFW simulations

Vairis and Frost[10] were the first to build a 2D model for LFW of Ti64 using Elfen, a FEA software program. For simplification purposes the problem was reduced to one where a deformable body was oscillating with friction against a rigid stationary body, taking benefit of the symmetries of joining similar material joints to reduce processing times. The predicted temperature was close to the recorded one.

In the report by Tao et al.[14], a thermo-mechanically coupled 3D model of LFW Ti64 was formed using the DEFORM 3D software. The process was also modeled in a simplified way employing a single oscillating workpiece and a rigid body, instead of two. Because the HAZ and deformation zone are both small, only a small zone near the bonding interface was selected for computation. The calculated temperature data and axial shortening of the joint were in agreement with experiments.

More recently, Fratini et al.[15] developed a 3D thermo-mechanically coupled model using DEFORM 3D for LFW ASTM A285 steel. Their model consisted of two workpieces as rigid-viscoplastic objects. The calculated axial shortening was comparable to the experimentally recorded one. Similarly, with increasing the frequency of oscillation and friction pressure more flash is formed and larger axial shortening is obtained.

Sorina-Müller et al.[16] conducted a full thermo-mechanically coupled transient 3D numerical analysis of Ti6246 using ANSYS. Ti6246 samples were forged in two different microstructures and two different cross-section geometries. It was found that the geometry of the contact interface affects the temperature distribution in the weld and the heat-affected zone with the maximum temperature occurring in the middle of the welding interface. As the HAZ is small, only part of the samples near the rubbing interface was selected for computation and meshed appropriately. The maximum temperature was found to increase from

20 ℃ to 1 100 ℃, well above the β-transus temperature, which indicated that no melting conditions were reached during the process, a fact which has been verified metallurgically. However, the deformation results were not accurate due to limitations by ANSYS in treating such problems.

Grujicic et al.[17] modeled LFW Ti64 with a fully coupled thermo-mechanical 3D model built using ABAQUS. They used the modified Johnson-Cook model to consider the dynamic recrystallisation with a user-material subroutine. To overcome element distortion, an Arbitrary Lagrangian Eulerian (ALE) formulation was used to maintain good quality mesh. Although the results concerning flash formation and temperature appear fine, the element size was coarse compared to the workpiece size.

Ceretti et al.[18] presented a 2D model of LFW AISI1045 steel using the DEFORM 2D software. The model is made of four objects, two for the chuck and two for the parts to be welded. The contact condition at the rubbing interface between the two specimens is a key parameter in any FE model as it affects frictional heat generation with the coefficient of friction. In this particular case it increased at the beginning and then remained constant. The estimated axial shortening was compared to experiments and found to be in agreement.

Li et al.[19-20] also developed 2D and 3D models for LFW using ABAQUS/Explicit. The coupled thermo-mechanical analysis used the Johnson-Cook material model which takes into account the effects of strain hardening, strain rate strengthening and temperature softening. The thermal and mechanical properties of the material and friction coefficient were temperature dependent. The models developed were versatile as they can be used for different materials in similar joint arrangements.

The effects of process parameters on temperature development and axial shortening of joints were investigated, and compared to experiments. As the oscillation frequency increases, the interface temperature reaches faster a maximum value and axial shortening reaches a larger value at a faster rate. However, when the oscillation frequency decreases, the temperature at the interface centre increases slowly, and the total axial shortening of the joint is considerably smaller than before with limited flash formed. The same relationships exist for changes in the amplitude and friction pressure. Nevertheless, it should be stated that the effects of these factors are not independent of each other and can be put together into a single factor of heat input. Heat input is proportional to oscillation frequency, amplitude and friction pressure. Analysing a large number of results from models, Li et al.[19-20] found that when the heat input is higher than a critical value, axial shortening will increase proportionally with increasing heat input. In conclusion, an appropriate level of heat input, i. e., proper combination of these three factors, is necessary to achieve a sound weld, which has been observed in experiments[12, 21-23].

During modeling of the process, the extruded flash is formed by deforming elements at the weld interface, where large strains inevitably cause excessive element distortion, which adds an additional difficulty in 3D models compared to 2D model. The method usually employed is the ALE (Arbitrary Lagrangian Eulerian) adaptive mesh control as it can maintain a high-quality mesh throughout the analysis. However, the capability of this method is limited at maintaining a high-quality mesh at very large deformations. In order to overcome the excessive element distortion problem in 3D models, Li et al.[19] developed an explicit-implicit alternate method, which combines the ALE adaptive mesh control in the ABAQUS/Explicit package with a map solution technique in the ABAQUS/Standard package using the HYPERWORKS software. The model was initially analyzed with the explicit package with an ALE adaptive mesh control. In the case of the analysis not finishing within the set time due to element distortion, then an orphan mesh is extracted of the last frame before excessive distortion and remeshed with HYPERMESH. Following this procedure, the new mesh is imported in ABAQUS and results from the last step are mapped to the new mesh with the standard ABAQUS package. After this, the analysis is run again with the explicit code till the end of the analysis.

In addition, Li et al.[24] also found an interesting "heat reflux" phenomenon by studying modeling and experimental results, where the heat is initially stored in the flash during the extrusion stage to be brought back later on to the workpiece during the cooling stage. Heat loss analysis showed that about 90% of the energy stored in the flash is lost through conduction to the workpiece during the cooling phase[24]. As stated by Li et al.[24], the heat reflux phenomenon could affect the microstructure of the weld root, and thus influence the mechanical properties of joints.

Turner et al.[25] formulated a 2D finite element model for Ti64 using the commercial code Forge, in which the workpiece was assumed to be in ph. III with a predefined temperature distribution while the model comprised of a single workpiece as at that stage it was assumed that the two workpieces were joined together. The authors used a point-tracking process to monitor the nodes of the weld line, to show that eventually all of them were fully extruded into the flash. The flash shapes predicted were very close to those observed in the experiments. However, the unconventional use of a single part to model the two workpieces may introduce errors in an effort to match results with experiments. In reality, the flash is extruded as a single body in the case of titanium alloys, while for many other materials, such as Al alloys and superalloys, it forms two separate pieces.

More recently, Song et al.[26] developed a novel framework for 2D LFW simulation using ABAQUS/Implicit, where they used an automatic Python code to apply the map solution and remeshing techniques which were applied to user-defined element and amplitude subroutines. Similarly the coupled thermo-mechanical model was employed with the Johnson-Cook material model. Actually, Li et al.[27] has used this technique in modeling inertia friction welding of superalloys in their earlier work. It appears that such material models are in good agreement with experiments. However, it might be difficult to complete the models without developing excessive interface element distortion when samples have large widths.

2.2 Other cases in LFW models

With numerical modeling, the temperature history, stress and strain fields during the process can be calculated. In addition to these, the modeling results can be used to analyse the microstructure (e.g. grain size in the nugget zone) developed[17], predict mechanical properties and calculate residual stresses[26, 28], and even study bonding in an atomic scale[29].

3 Summary and outlook

This review has critically presented the vast majority of papers published on modeling of LFW. Although the process is available for more than 20 years, it still remains a niche process both in research and in manufacturing. To date, the production of blisks in the aeroengine industry is the only commercial application.

Welding parameters play an important role in the success of the process and the microstructure formed. There is a minimum value of power input necessary for every material for the production of sound welds. The power input to the welding interface is determined by these parameters, which do influence the temperature developed during welding.

During the process, the material across the rubbing interface, which has yielded locally due to the high temperature and stress conditions, is extruded to form a flash which is a typical phenomenon in LFW and in the majority of the cases reflects the quality of the weld. Many papers have been written on the macroscopic features of the flash, but there is no study on the microstructure of the flash, associating it to the temperatures reached.

Numerical analysis using advanced computational tools can be used to provide insight into such a complex process. As modeling of heat generation is becoming mature researchers have been developing 2D and 3D models for LFW using different numerical analysis software. Most of the research on modeling has been on temperature history with it being matched to experiments. However, a lot of modeling still remains to be performed. The following open ended questions need to be addressed in the future to successfully model all aspects of the process.

The first question is excessive element distortion. As the process is very complex, the models developed for LFW can not model the whole process from start to finish. The meshless method may provide an effective way to model the whole process.

The second question to be addressed is bonding of the welding interface. Although a lot of analyses[10, 18, 20] have assumed that the upper and lower components are symmetrical and have ignored interface bonding, the flash is indeed produced by the upper and lower components as a whole and it is truly asymmetrical.

The last question relates to flash shapes and ridges. In experiments, an asymmetrical flash with typical ridges is extruded from all sides, especially from the oscillation direction. However, there is no published work which has calculated the actual shape of the flash by modeling the process from the start. The analysis of the flash may be helpful in understanding the bonds formed during the process.

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