Hindawi Publishing Corporation
Advances in Materials Science and Engineering
Volume 2014, Article ID 521937, 8 pages
http://dx.doi.org/10.1155/2014/521937

Review Article

The Importance of Materials Data and Modelling Parameters in an FE Simulation of Linear Friction Welding

R. Turner,[1] F. Schroeder,[1,2] R. M. Ward,[1] and J. W. Brooks[1]

[1] *School of Metallurgy & Materials, The University of Birmingham, Edgbaston, Birmingham B15 2TT, UK*
[2] *Hilti Corporation, 9494 Schaan, Liechtenstein*

Correspondence should be addressed to R. Turner; r.p.turner@bham.ac.uk

Received 10 January 2014; Accepted 11 January 2014; Published 26 February 2014

Academic Editor: Wenya Li

Linear friction welding has become a key technology in the aeroengine industry due to its capability to produce blisk components. Finite element (FE) simulation of linear friction welding applications has been studied in recent years by a number of institutions, using a variety of software codes. Several codes have been demonstrated to be capable of predicting with reasonable accuracy some or all of the critical outputs of friction welding, namely, the thermal loading, plastic deformation, and residual stresses generated. The importance of reliable material data in performing these calculations is paramount. Available material data in the published literature is often restricted to lower temperatures and strain rate regimes. Extrapolation methods used on this data to estimate high temperature properties can lead to uncertainties in the modelled predictions. This paper reviews the approach to materials modelling, including material datasets and material constitutive laws, for FE simulation work in the literature regarding linear friction welding. Best-practice methods for materials constitutive laws, materials data-sets, and the associated experimental temperatures and strain rates used to gather data are suggested. Finally, successfully validated modelled outcomes—when a robust, reliable, and accurate material database has been selected—are demonstrated for a number of the FE methods considered.

1. Introduction

Linear friction welding is a solid-state joining process which, if successfully implemented into the civil aeroengine industry, could allow for a significant reduction in the weight of these engines and in turn produce benefits in performance, economy, and emissions [1]. This is achieved by replacing the dovetail mechanical joint that holds the blades to the discs with a weld line—to form an integrally bladed disc or blisk component [2]. The process has been well described within the literature, in terms of its process parameters and the process phases [3]. Whilst much of the research has been focused upon microstructural characterisation and weld quality, a number of papers have considered the governing process physics and used FE analysis to better understand these process fundamentals. Linear friction welding is an ideal method of joining components, such as the blisk, given the nonaxisymmetric nature of the joint and the size of the component. In essence, the process consists of holding one component stationary, whilst linearly oscillating a second component, with the two in contact and under an applied normal force, as illustrated in Figure 1.

Whilst solid-state welding methods are not the only processing route for such a component—mechanical fixturing of the blade-root such as a dovetail joint and machining from solid would also be possibilities—there are distinct benefits that a solid-state weld such as linear friction welding offers. These include: (i) the capability to join together different materials or to join hollow blades to the disc—something that machining from solid could not achieve [4]—and (ii) a significant reduction in component weight in comparison to a mechanical fixturing at the blade-disc interface.

1.1. FE Simulation Methods in the Literature. Process modelling of linear friction welding has been studied in recent years by a number of academic and industrial organisations [5–15], with various FE software packages demonstrated to be reasonably capable of representing this joining technology, including DEFORM [9–11, 14], FORGE [13], Elfen [5],

Table 1: Details of current LFW FE simulation publications, their material formulation, meshing used, and validation methods.

Publication	Software	Dimension	Finest mesh size [mm]	Material data	Validated results
Vairis and Frost [5]	ELFEN	2D	n/a	Tabular	Temperatures and shear stress
Li et al. [6]	ABAQUS	2D	0.5	Johnson-Cook	n/a
Ceretti et al. [10] Fratini et al. [9], Fratini and La Spisa [11]	DEFORM	2D, 3D	0.6 0.5, 0.25	Tabular Equation-based	Upset rate
Sorina-Müller et al. [12]	ANSYS	3D	0.125	Tabular	Upset rate
Turner et al. [13]	FORGE 2008	2D	0.25	Tabular & Norton-Hoff	Flash morphology, temperatures upset rates, and residual stress
Schroeder et al. [14]	DEFORM	2D	0.08	Tabular	Temperatures, upset rates, and flash morphology

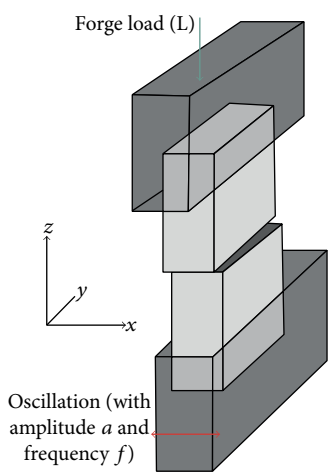


Figure 1: Schematic of a linear friction weld, showing the testpieces, tooling, and axes of motion.

ABAQUS [6–8], and ANSYS [12, 15]. Table 1 summarises the literature on FE simulation of the LFW process. However, the accuracy of any such models will depend upon the input data, including the mesh used (see Figure 2), thermal profiles (if these are not predicted internally), boundary conditions employed to replicate the tooling and clamping, and the materials data used to describe the alloys being joined. Given that this technology is so far most widely used in aeroengine industries, most of the research to date has been focused upon the traditional aerospace materials: titanium alloys [5, 6, 12–14], nickel alloys, and steels [9–11]. The linear friction welding process must be modelled as a fully coupled thermal-mechanical analysis as the heating produced by the shearing and deformation of the material is necessary for the process to operate.

A purely analytic solution to the thermal field arising during a friction welding process was proposed by Grong [16]; however, the first attempt at an FE simulation of the LFW process was made by Vairis and Frost [5], in which groundbreaking research within this field was made. The model was computed in Elfen, using a mesh of 764 elements, a considerable computational problem for the computers of the time. The model was reduced to consider just a half of the welded joint, one side of the weld line. Materials data for the alloy Ti-6Al-4V was entered into the model in tabular format, at limited temperatures, with the software interpolating data for other temperatures. A linear decay of yield stress with increasing temperature was assumed. Other materials data was entered at the average values for the temperature range anticipated. The model achieved reasonable correlation for thermal predictions when compared to thermocouple measurements; the authors comment that thermocouples can underestimate the actual conditions due to the limited control over the thermal inertia, the response time, and the positioning of the junction in the specimen. It was demonstrated that a purely analytic model with assumed temperature-independent material properties predicted significantly higher temperatures than the FE model. It was also first stated that the sparks produced during the process were of negligible impact upon the process, meaning that FE simulation of the component, ignoring losses through this exothermic reaction, would be sufficient.

Li et al. [6–8] published work on 2D LFW modelling of a titanium alloy in ABAQUS, suggesting that temperatures achieved during linear friction welding were higher than Vairis proposed, reaching approximately 1000°C before achieving a relatively steady state. The materials data that was implemented into the model by Li used the Johnson-Cook law to describe the material flow-stress behaviour, given in

$$\sigma_y = \left[A + B\left(\varepsilon_p\right)^n\right]\left[1 + C\ln\left(\dot{\varepsilon}_p^*\right)\right]\left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right], \quad (1)$$

where σ_y is the flow-stress, ε_p is the plastic strain, $\dot{\varepsilon}_p^*$ is the normalised plastic strain rate, T_0 is a reference temperature,

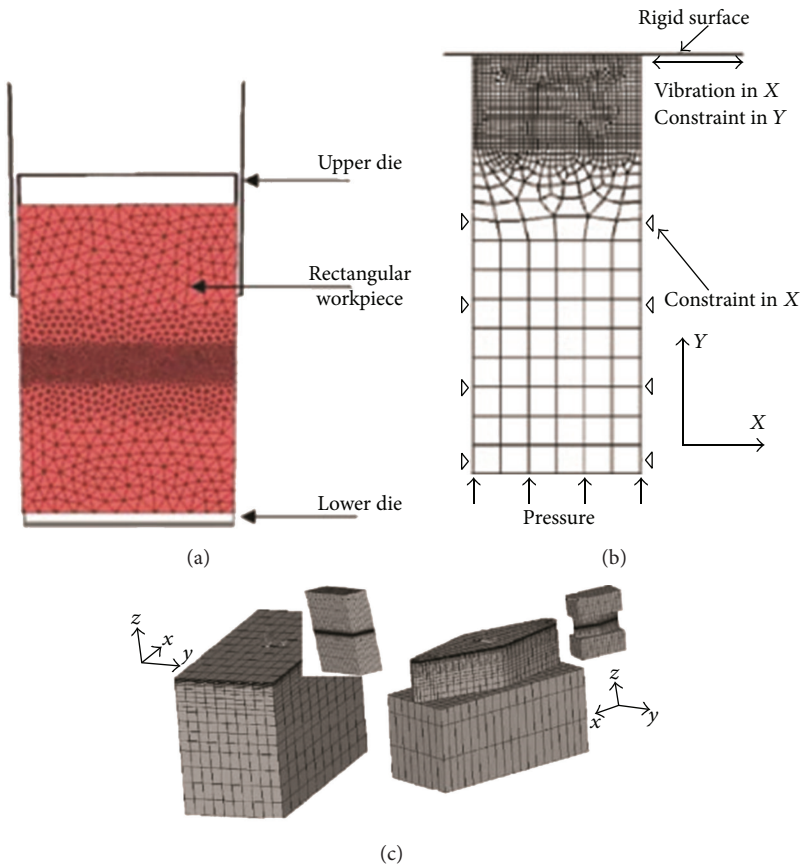


Figure 2: Diagrams showing the meshing used typically for a 2D testpiece LFW process model in various LFW FE simulations: (a) 2D simulation of both sides of the joint, (b) 2D simulation of 1 side of the joint, and (c) 3D simulation.

T_m is a melting temperature, and A, B, C, m, and n are material constants. Values assigned to A, B, C, m, and n are detailed within literature [6]. A temperature-independent density and Poisson ratio were used. Temperature-dependent measurements of properties such as thermal conductivity and heat capacity were included. However, measured data available within the literature commonly only reaches temperatures of 600°C, and as such extrapolation methods are required to estimate materials properties higher than this. Li et al. estimated materials properties up to 1000°C. Therefore, should the predicted temperature at any node exceed 1000°C, the software would be required to extrapolate outside of its known database. The mesh employed by Li et al, shown in Figure 2, was finer than that of the ELFEN model, owing largely to the far superior computing power available to the researchers compared to a decade before. Elements at the weld line were 0.5 mm in length, coarsening gradually away from the weld. The ABAQUS model was again considering one half of the weld only. It is probable that the refined element size was the key contributor to increasing the modelled weld line temperatures, owing to the steep thermal gradient located close to the weld. Larger elements would not be capable of capturing the resolution of such steep thermal gradient over such a small distance.

Fratini and Ceretti et al. [9–11] developed a modelling capability using the software package DEFORM by SFTC. Work presented using a 2D approach [10] had a tabular AISI 1045 steel material file from the software's material library and a mesh with a minimum element size of 0.6 mm. Temperatures were generated using a time dependent shear factor at the interface. The results were validated in terms of upset rate; however, the flash morphology predicted by the model was not validated. The thermal gradient at the weld interface was approximately 900°C across 9 elements with a peak gradient of about 600°C across 3 elements. With thermal gradients being this high, material properties are likely to vary considerably across the size of an element which could limit the accuracy of the model (examples of a typical tabular input for the thermal conductivity and specific heat for Ti-6Al-4V found in literature [17] are given in Figure 3). This could be confirmed by consideration of the data or a mesh sensitivity study. A 3D model was presented by the authors [9] applying an equation-based material formulation and a minimum mesh size at the weld interface of 0.5 mm [10] which was further reduced to 0.25 mm in [9]. A temperature-dependent shear friction coefficient was assumed; however, it is not clear how this was determined. Predicted upset rates from the 2D and 3D models were compared to experimental results and displayed better agreement for three dimensional models. The model with reduced mesh size was interrogated for predicted weld interface temperatures at different process parameters, and these were compared to

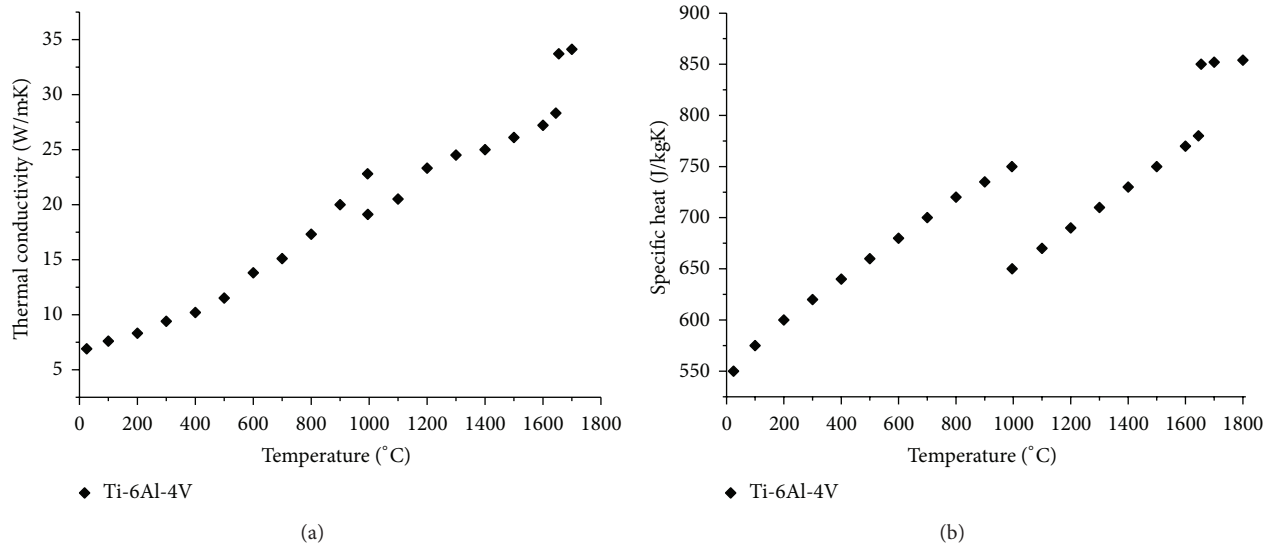


Figure 3: Titanium alloy data available within the literature [17] for (top) thermal conductivity and (bottom) specific heat.

data from experiments. A comparison of the upset was made, demonstrating reasonable agreement during the initial stage; however, constant upset during the equilibrium phase of the process appears higher in the experiment compared to the model.

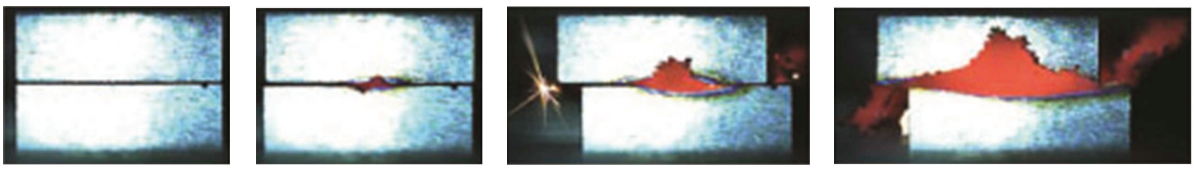
Sorina-Müller et al. [12] presented an ANSYS 3D model of linear friction welding of titanium alloys. They developed work from simple block geometry to a small-scale "blade-like" geometry. The mesh employed in the ANSYS model contained elements with length 0.125 mm at the weld and gradually coarsened away from the weld—see Figure 2. The model was primarily validated using axial shortening data from experiments. Materials data was entered into the ANSYS model as a temperature-dependent tabular format. Materials tests, including dilatometry, differential scanning calorimetry, and the laser flash method, were employed to determine the thermal expansion, heat capacity, and thermal diffusivity, respectively. It was recommended that materials properties should be measured or estimated up to temperatures of approximately 1250°C. This would prevent any unwanted software extrapolation of results—so long as modelled temperatures do not reach this high. Peak temperatures at the weld line will be dependent upon process parameters. Hence, the material database will need to consider the LFW process parameters to ensure that the model remains within the range of input data. The rigorous approach to materials modelling produced an FE model which agreed well with experiments. Sorina-Müller et al. also state that their linear friction welding simulation would be capable of considering different material conditions on either side of the weld line, specifically a different processing route for the titanium alloys to produce subtly different material. This would suggest that a full model, rather than half-model, would produce a more rigorous modelling approach, when considering industrial materials and components.

Turner et al. [13] proposed a 2D FE simulation using a plane-strain mode, using FORGE2008. This model considered the full weld, as opposed to just half, and represented the joining of the alloy Ti-6Al-4V to itself. As with other work, a graded mesh was employed—see Figure 2 for a comparison of meshes. The material data used to perform the FE calculations came from Sente software's JMatPro database. This data included a tabular flow-stress input deck for varying strains (0.01 to 4), strain rates ($0.001\,\mathrm{s}^{-1}$ to $1000\,\mathrm{s}^{-1}$), and temperatures (25°C to 1200°C); tables for thermal conductivity, thermal expansion, specific heat, density, and Poisson's ratio—all as a function of temperature (25°C to 1200°C). Upon analysis of the FE model, strain rates predicted by the model at the weld line were reported to be as high as $2500\,\mathrm{s}^{-1}$ for certain modelling conditions, although generally they were below $1000\,\mathrm{s}^{-1}$. This could have led to unwanted extrapolation of data as processing conditions were occasionally out of the specified input range. It was noted that, in the FORGE2008 work, the models which used the tabular data offered the more accurate solutions for all outputs (i.e., temperature, residual stress, and distortion), when compared to models based on the Norton-Hoff equation:

$$\sigma_y = \sqrt{3}^{(m+1)} K \varepsilon^n \dot{\varepsilon}^m e^{-\beta T}, \tag{2}$$

where σ_y is the flow-stress, ε is the plastic strain, $\dot{\varepsilon}$ is the plastic strain rate, T is the material temperature, and m, n, K, and β are material constants.

Despite potentially increasing the computational demand, a tabular dataset can excel in accurately representing the material behaviour at a wide range of processing conditions [18]. Equation-based approaches—and the coefficients considered—must be carefully selected to produce the same successful outcome. An equation-based material flow-stress law, such as the Johnson-Cook or the Norton-Hoff, may struggle to accurately reflect material behaviour for a wide range of both temperature and strain rate. However, the equation-based approach does remove any need for data



(a) (b) (c) (d)

Figure 4: High-speed photography of a titanium alloy linear friction weld [14].

interpolation—something which is reliant on the software rather than the material model and is more computationally efficient than a tabular method. It is important for the tabular dataset to be well populated—as titanium alloys such as Ti-6Al-4V are known to undergo a rapid degradation of mechanical and structural properties [19] at elevated temperatures. A well-populated dataset would be able to represent this rapid degradation by a sensible distribution of data points. However, for both a tabular and an empirical equation-based fit, there is no capture of the thermomechanical processing history effects. The full impact upon microstructure and material properties of work-hardening or the heat treatment undergone during the rapid heating within a friction weld is something that these approaches do not consider, and a microstructural modelling capability would be required if these effects were to be incorporated within the modelling framework.

The model from [13] was developed further by Schroeder et al. [14] in DEFORM, again considering a 2D plane-strain methodology, targeting the different process phases of conditioning and equilibrium. Thermal profiles generated during conditioning were predicted and subsequently validated to establish an initial condition for the equilibrium model. It was shown that the temperatures depend on not only process parameters but also the shape of the thermal profile. Thermal loading at the weld line during equilibrium was suggested to be even higher than previously measured or modelled (subject to weld parameters used), with weld line temperatures exceeding 1200°C predicted. Thermal measurements made with thermocouples confirmed temperatures exceeding 1200°C. High-speed photography methods were implemented to better understand the fundamental process physics associated with material extrusion and flash formation. These images were then compared to the modelled predictions for flash formation mechanisms. Still images from the high-speed photography are presented in Figure 4 [14].

Research by Kiselyeva et al. [15], using the popular FE code ANSYS, has explored the 2D simulation of the equilibrium phase of a linear friction weld. The titanium alloy being modelled was assumed to have an isotropic elastic material model during the heating stage, switching to a viscoelastic model to accurately predict the deformation and flash formation. Although element size at the weld line is not quoted, it appears to be of a similar size to those used in other ABAQUS and DEFORM linear friction weld models.

2. Results and Discussion

Once an established material modelling database has been created and incorporated into the FE model, the model outputs can be studied. The DEFORM models by Schroeder et al. [14], the FORGE models by Turner et al. [13], the ANSYS models by Sorina-Müller et al. [12], and the ABAQUS models by Li et al. [6–8] were all analysed for their predicted temperatures at the weld line. Each model predicted that weld line temperature would exceed 1000°C—subject to the welding process parameters—offering reasonable assurances that the FE models, whilst built in different software codes, utilising different methods of modelling the associated material, were considering the correct physical processes and mechanics to simulate the weld. All modelling techniques considered the heating within the component via plastic deformation during steady-state welding. The thermal results are presented in Figures 5(a), 5(b), and 5(c) and demonstrated the localised nature of heating. The FORGE models, considering different applied axial loads, predict the peak weld line temperatures varying from weld to weld by ~100°C. The mechanism of extruding the hot material out of the weld and into the flash maintains a reasonably constant thermal profile across the three welds.

It is important to understand which of the modelled outputs are considered critical to the success of an FE model. The different papers sought to validate their models using different outputs, such as upset rates, flash morphology, residual stresses, and temperatures to validate the models.

Within their 2D linear friction welding simulations considering both sides of the weld, Turner et al. and Schroeder et al. targeted upset rates, thermal loads, and accurate flash morphology. Other FE models studied in the literature have less accurate flash formation morphology prediction, but this may not have been targeted as an important output for them. Flash formation could be considered an output of secondary importance, given that it will not form any part of the final weld condition in a real component. However, the possibility of material being dragged back inside the weld after being exposed to the atmosphere would suggest that flash formation is a potentially critical model output. Turner et al., and in turn Schroeder et al., targeted flash morphology accuracy to provide a visual verification that their FE models were considering the correct deformation modes and that material data was reasonable. Flash morphology gives reasonable insight into the welding process

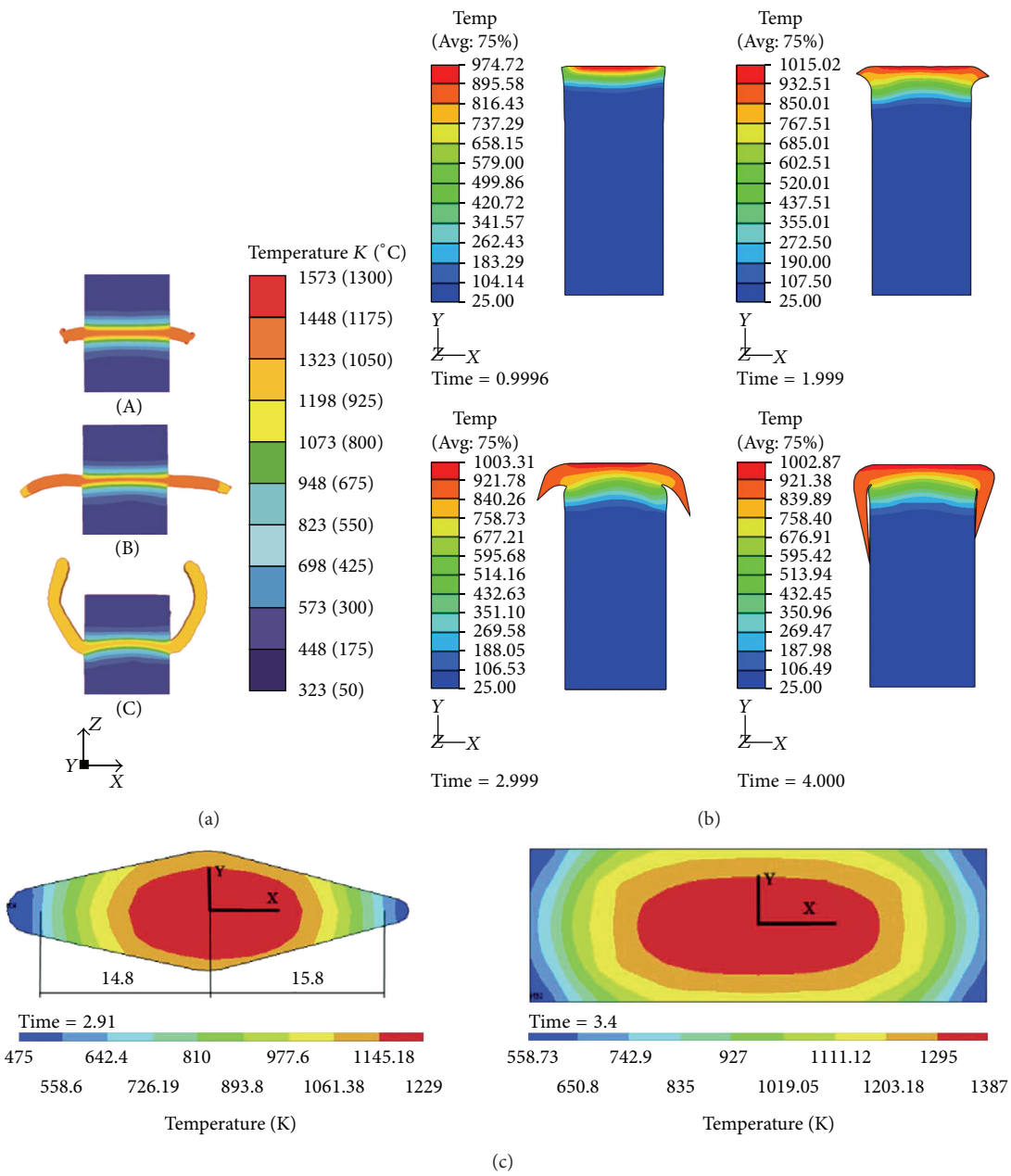


Figure 5: (a) Thermal profiles predicted for 2D LFW simulation considering both sides of the weld, at three different pressures: (A) low pressure, (B) medium pressure, and (C) high pressure [13]. (b) Thermal profile predicted for 2D LFW simulation considering only one side of the weld, for Ti-6Al-4V, at different times during the process [6]. (c) Thermal profile on the weld interface for a 3D LFW simulation, considering a "blade-representative" geometry [12].

and can potentially allow for initial assessments of weld line quality. Figure 6 illustrates the predicted flash morphology within the models, for (top) low amplitude and high pressure and (bottom) high amplitude and low pressure welds, and compares the modelled predictions to similar experimental welds. The nature of the flash morphology between modelled prediction and experiment is similar. The distinct rippling observed in the 2nd case suggests that the flow-stress tabular input for Ti-6Al-4V used in these FE models has captured the correct flow and behaviour properties of this material, relating to the deformation mode of the flash as it is extruded from the weld line. Flash formation and material extrusion resulting in parameter specific upset rates are the product of accurate material data and temperatures. Comparison of upset rates of models and experiments showed they were in good agreement over a wide range of parameters.

3. Conclusions

FE simulation of linear friction welding is currently being driven predominantly by aeroengine manufacturers, often through their associated academic partners, due to the

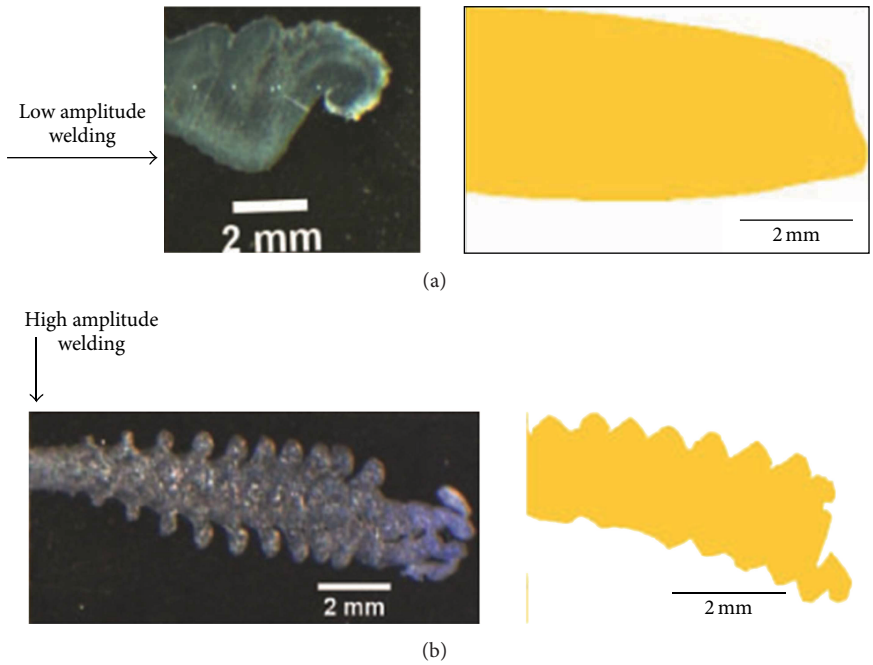


Figure 6: Examples of flash formation during LFW; top: smaller amplitude and high applied load and associated modelling; bottom: large amplitude and lower applied load and associated modelling [14].

importance of this process in producing high-value blisk components. Probably related to the locations of the technology centres for these aeroengine manufacturers, research institutions in the UK, the USA, Germany, and China have published simulation work on LFW in recent years, developing the initial model created by Vairis et al., first reported in 1998. When constructing an FE model of LFW, it is important that the intended outputs of the model are considered carefully, by appropriate choices regarding the material database and the modelling parameters such as meshing. With the computational developments over the last decade, modern FE models have the potential to work in much greater detail than previously. This detail could take the form of a finer weld line mesh—if required for the desired model outputs—or real component geometry, as opposed to the simple rectilinear testpieces often used in simulations.

The authors have reviewed the current state of FE simulations of the linear friction welding process and in particular the approach to the materials modelling database and the meshing strategy that each FE method used. The following conclusions are made.

(i) Several general FE software codes have been demonstrated capable of simulating linear friction welding. Whilst each code may require some detailed knowledge to accurately replicate the process, such as the oscillating motion and the merging of separate meshes, experienced FE users can often adapt these generic codes for their specific purposes.

(ii) Both tabular and equation-based flow-stress models have been successfully implemented in a linear friction weld simulation. Each method offers different benefits to the simulation; the tabular approach generally appears to be a more robust and reliable method than the empirically fitted equations chosen to represent various materials so far, whilst an empirical equation-based approach offers greater computational efficiency than tabular.

(iii) For a tabular approach, data should be sufficient such that the model never has to extrapolate outside of the defined range. In the case of strain rate, it is suggested that data up to $2000\,s^{-1}$ is included. In the case of temperature, the peak temperatures predicted by the model will depend upon process parameters. Generally however, 1300°C should certainly be an acceptable upper limit for the datasets for Ti-6Al-4V.

(iv) Meshing strategies should be tailored according to the desired modelling outputs. If accurate material flow behaviour is required, and as such flash morphology is considered important, then a fine mesh at the weld line is recommended, with elements potentially as small as 0.1~0.2 mm edge length. If thermal and upset results only are important, then potentially the weld line elements can be larger.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

References

[1] J. C. Williams and E. A. Starke Jr., "Progress in structural materials for aerospace systems," *Acta Materialia*, vol. 51, no. 19, pp. 5775–5799, 2003.

[2] P. Wanjara and M. Jahazi, "Linear friction welding of Ti-6Al-4V: processing, microstructure, and mechanical-property interrelationships," *Metallurgical and Materials Transactions A*, vol. 36, no. 8, pp. 2149–2164, 2005.

[3] A. Vairis and M. Frost, "High frequency linear friction welding of a titanium alloy," *Wear*, vol. 217, no. 1, pp. 117–131, 1998.

[4] M. E. Nunn, "Aero-engine improvements through linear friction welding," in *Proceedings of the 1st International Conference on Innovation and Integration in Aerospace Sciences*, Queen's University Belfast, Northern Ireland, UK, 2005.

[5] A. Vairis and M. Frost, "Modelling the linear friction welding of titanium blocks," *Materials Science and Engineering A*, vol. 292, no. 1, pp. 8–17, 2000.

[6] W.-Y. Li, T. Ma, and J. Li, "Numerical simulation of linear friction welding of titanium alloy: effects of processing parameters," *Materials & Design*, vol. 31, no. 3, pp. 1497–1507, 2010.

[7] W. Li, S. Shi, F. Wang, Z. Zhang, T. Ma, and J. Li, "Numerical simulation of friction welding processes based on ABAQUS environment," *Journal of Engineering Science and Technology Review*, vol. 5, no. 3, pp. 10–19, 2012.

[8] W. Y. Li, S. X. Shi, F. F. Wang, T. J. Ma, D. Guo, and A. Vairis, "Heat reflux in flash and its effect on joint temperature history during linear friction welding of steel," *International Journal of Thermal Sciences*, vol. 67, pp. 192–199, 2013.

[9] L. Fratini, G. Buffa, D. Campanella, and D. La Spisa, "Investigations on the linear friction welding process through numerical simulations and experiments," *Materials & Design*, vol. 40, pp. 285–291, 2012.

[10] E. Ceretti, L. Fratini, C. Giardini, and D. La Spisa, "Numerical modelling of the linear friction welding process," *International Journal of Material Forming*, vol. 3, no. 1, pp. 1015–1018, 2010.

[11] L. Fratini and D. la Spisa, "Numerical simulation of Linear Friction Welding (LFW) processes," in *Proceedings of the 14th International Conference on Material Forming (ESAFORM '11)*, vol. 1353 of *AIP Conference Proceedings*, pp. 1284–1289, Belfast, UK, April 2011.

[12] J. Sorina-Müller, M. Rettenmayr, D. Schneefeld, O. Roder, and W. Fried, "FEM simulation of the linear friction welding of titanium alloys," *Computational Materials Science*, vol. 48, no. 4, pp. 749–758, 2010.

[13] R. Turner, R. M. Ward, R. March, and R. C. Reed, "The magnitude and origin of residual stress in Ti-6Al-4V linear friction welds: an investigation by validated numerical modeling," *Metallurgical and Materials Transactions B*, vol. 43, no. 1, pp. 186–197, 2012.

[14] F. Schroeder, R. M. Ward, R. Turner, M. M. Attallah, J.-C. Gebelin, and R. C. Reed, "Linear friction welding of titanium alloys for aeroengine applications: modelling and validation," in *Proceedings of the 9th International Trends in Welding Research Conference*, 2012.

[15] S. K. Kiselyeva, A. M. Yamileva, M. K. Karavaeva et al., "Computer modelling of linear friction welding based on the joint microstructure," *Journal of Engineering Science and Technology Review*, vol. 5, no. 3, pp. 44–47, 2012.

[16] O. Grong, *Metallurgical Modelling of Welding*, Cambridge University Press, Cambridge, UK, 1994.

[17] K. C. Mills, *Recommended Values of Thermophysical Properties for Selected Commercial Alloys*, NPL, Woodhead, 2002.

[18] Z. Guo, R. Turner, A. da Silva et al., "Introduction of materials modelling into processing simulation," *Materials Science Forum*, vol. 762, pp. 266–276, 2013.

[19] S. Zherebtsov, G. Salishchev, R. Galeyev, and K. Maekawa, "Mechanical properties of Ti-6Al-4V titanium alloy with submicrocrystalline structure produced by severe plastic deformation," *Materials Transactions*, vol. 46, no. 9, pp. 2020–2025, 2005.