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Linear friction welding process simulation of Ti-6Al-4V alloy: a heat transfer analysis of the conditioning phase

Samuel Bertrand*, Davood Shahriari, Mohammad Jahazi*, Henri Champlaud

École de Technologie Supérieure, Département de Génie Mécanique, Montréal, H3C 1K3, Canada

Abstract

Linear Friction Welding is an emerging solid-state joining process used for complex geometries. The process is composed of four distinct phases: conditioning (also called initial), transition, friction, and forging. This paper proposes a new numerical approach to simulate the initial phase (phase 1) while reducing the computational time. An implicit fully coupled thermomechanical 2D analysis scheme in ABAQUS was employed to compare the proposed thermal model and the conventional oscillation model. Physical and mechanical temperature-dependent properties of Ti-6Al-4V were implemented in the two models. An excellent agreement was obtained with the experimental temperature profiles published in the literature. The new thermal model reduces the computational time significantly, up to 99% with respect to an oscillating model.

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Keywords: Linear Friction Welding; Heat transfer; Finite Element Analysis; Variable friction coefficient; Subroutine

1. Introduction

Linear Friction Welding (LFW) is a developing solid-state joining process that is being adopted for the manufacturing and repair of complex components, such as blade integrated disks (blisks) in turbines or aircraft engines. The transport and energy industries have a growing interest in this technology for its rapidity and its cost savings. The process is fast, conducted in few seconds [1], and it does neither require filling element nor gas shield

* Corresponding authors. Tel.: +1-514-396-8974 ; Fax: +1-514-396-8530

E-mail address: samuel.bertrand@mines-saint-etienne.org

E-mail address: mohammad.jahazi@etsmtl.ca

protection compared to traditional welding methods. As a result, the manufacturing costs are reduced [1, 2]. The LFW process can be decomposed into four phases: initial, transition, friction, and forging phase. The temperature increases rapidly in the initial phase due to the solid-friction between the two workpieces. It leads to the thermo-mechanical threshold temperature in which the material at the interface is softened and can no longer sustain the contact pressure. Consequently, the material is expelled, and flashes are formed. Then the temperature and the extrusion rate reach a steady state. Finally, the oscillations are stopped, and the forging pressure is preserved or increased to consolidate the joint [2-4].

Numerical models allow to study and optimise the LFW processing parameters. Different numerical approaches have been already used [5]. Implicit and explicit solution schemes have been employed to carry out LFW simulation but the calculation time varies from hours to days [3]. In this paper, the initial phase (phase 1) is simulated and analysed. During this phase, the two workpieces have a reciprocal motion which generates frictional heat. A sufficient heat-input is a prerequisite for plasticising the material at the weld line which is a crucial parameter to have a sound joint. The axial shortening and the deformation are considered to be negligible in this phase compared to those occurring in the other phases. This study proposes a new method to reduce the computation time, and its efficiency is compared with the conventional oscillation models as well as experimental results.

2. Assumptions

The initial phase of LFW process is a critical phase because it produces the essential thermal energy to soften the material at the interface, which allows for preliminary joining of the interface. If the temperature at the weld interface does not reach the threshold point, the two workpieces will not be appropriately joined, resulting in a weak weld. The initial phase aims to reach the thermo-mechanical limit of the material close to the interface.

2.1. Ti-6Al-4V properties

The LFW model used a Ti-6Al-4V titanium alloy grade which is selected for blisks. For the modelling purposes, the material is considered to be homogeneous and isotropic. Additionally, temperature-dependent properties, physical and mechanical, were implemented in the model. These properties such as density, thermal conductivity (Fig. 1(a)), specific heat (Fig. 1(b)), Young's modulus, and the peak flow stress were obtained from both literature and Transvalor FORGE® NxT 1.1 software's [6] library and implemented in ABAQUS 6.14. The flow stress in Ti-6Al-4V during hot deformation depends on temperature, strain, and strain rate. During LFW, temperature and strain rate continually increase, leading to changes in the flow stress. Therefore, it is essential to implement a material constitutive model to predict flow stress during the process. The Johnson-Cook model takes into account the effects of strain, strain rate hardening and also thermal softening. So, the flow stress at each simulation step can be quickly computed. This model for various materials has been already employed to simulate LFW process [7-11]. According to the Johnson-Cook model, the flow stress (σ_y) of material could be expressed by Eq. (1), and its constants are summarised in Table 1.

$$\sigma_y = [A + B(\bar{\epsilon}^{pl})^n] \left[1 + C \log \left(\frac{\dot{\bar{\epsilon}}^{pl}}{\dot{\bar{\epsilon}}_0^{pl}} \right) \right] \left[1 - \left(\frac{T - T_0}{T_M - T_0} \right) \right]. \quad (1)$$

Table 1. Johnson-Cook material model parameters for Ti-6Al-4V [7].

Parameter	Symbol	Units	Value
Reference strength	A	MPa	418.4
Strain-hardening parameter	B	MPa	394.4
Strain-hardening exponent	n	N/A	0.47
Strain rate coefficient	C	N/A	0.035
Room temperature	T_0	°C	25
Melting Temperature	T_M	°C	1660
Temperature exponent	m	N/A	1
Strain rate of reference	$\dot{\bar{\epsilon}}_0^{pl}$	s ⁻¹	1

Ti-6Al-4V is an alpha-beta titanium alloy. The key to a successful hot deformation of this alloy is the beta transus temperature which is approximately 995 °C. The peak flow stress (Fig. 2) for Ti-6Al-4V alloy drops steeply from 750°C to 960°C and then shows steady-state behaviour after beta transus temperature. That reduction indicates the material has reached its thermo-mechanical threshold and it is relatively soft to allow the bonding between the two parts, under the friction pressure. On this basis, in this study, it was assumed that the initial phase was completed when the interface temperature reached the beta transus temperature of 960 °C ($\sim 0.6T_M$).

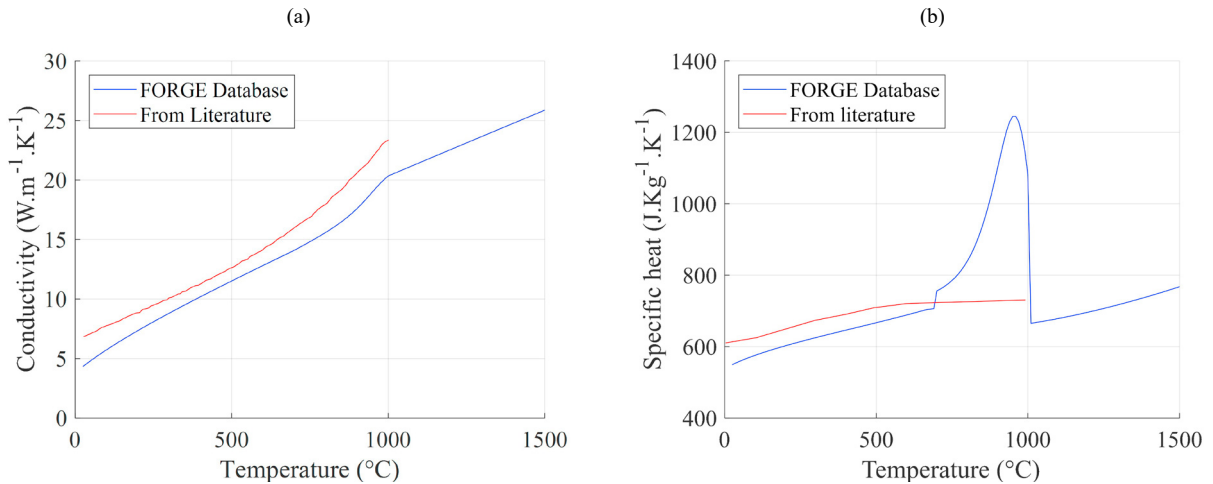


Fig. 1. (a) Thermal conductivity of Ti-6Al-4V reproduced from FORGE® library (in blue) and literature [8] (in red) and (b) heat capacity for Ti-6Al-4V reproduced from FORGE® library (in blue) and literature [9] (in red).

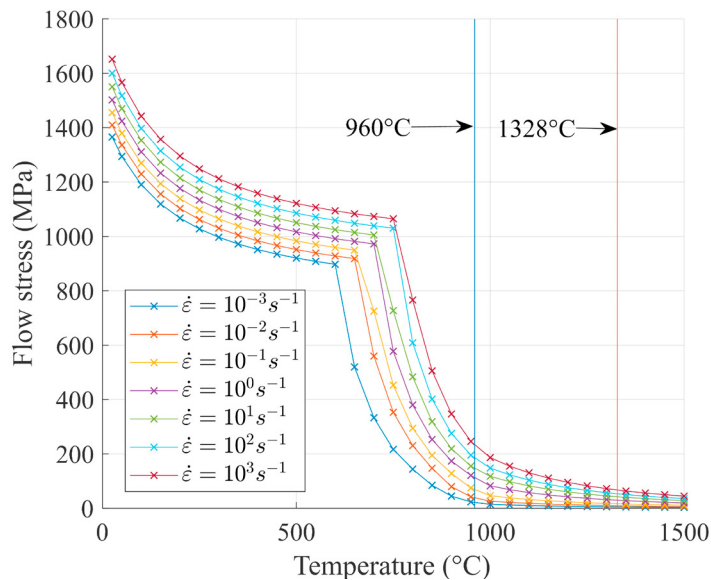


Fig. 2. Peak flow stress of Ti-6Al-4V depends on strain rate and temperature reproduced from FORGE® library.

2.2. Frictional Heat

Based on previous studies [2, 8, 12-14] the frictional heat during LFW process is generated between the two

contact surfaces (rubbing surfaces) in reciprocal motion under friction pressure. Also, the heat loss on the generated thermal energy due to radiation and convection is neglected. The average frictional heat (HI) can be expressed as:

$$HI = 4\mu A f p_n [\text{W.m}^{-2}], \quad (2)$$

where μ is the Coulomb's friction coefficient, A , f and p_n are respectively the amplitude, oscillation frequency and contact pressure. The friction coefficient is a function of several factors such as interface temperature, contact pressure, surface topology, etc. In this study, the Coulomb's friction coefficient is assumed to be affected by the rubbing surfaces and the temperature (Fig. 3). This study suggests to calculate the average frictional heat according to the process parameters and to apply it directly on the rubbing surfaces. It differs from the oscillating method where the frictional heat is determined at each time step according to the shear stress at the interface and the relative velocity of the two parts.

3. Numerical models

A 2D model was implemented in ABAQUS/STANDARD software. As shown in Fig. 4, the model is divided into two parts: lower and upper part. Each of them is a deformable body and has a length of 26 mm, a width of 13 mm, and a height of 26 mm. They are divided into three zones: the Heat Affected Zone (HAZ), the Thermo-Mechanically Affected Zone (TMAZ), and the parent material. The first two zones start at the welding line and spread up to 8 mm [2] then reach the parent material where no plastic deformation occurs throughout the LFW process. An element size of 0.5 mm was taken in the TMAZ and HAZ in agreement with [7], and the remainder of the workpiece was meshed to an element size of 2.5 mm.

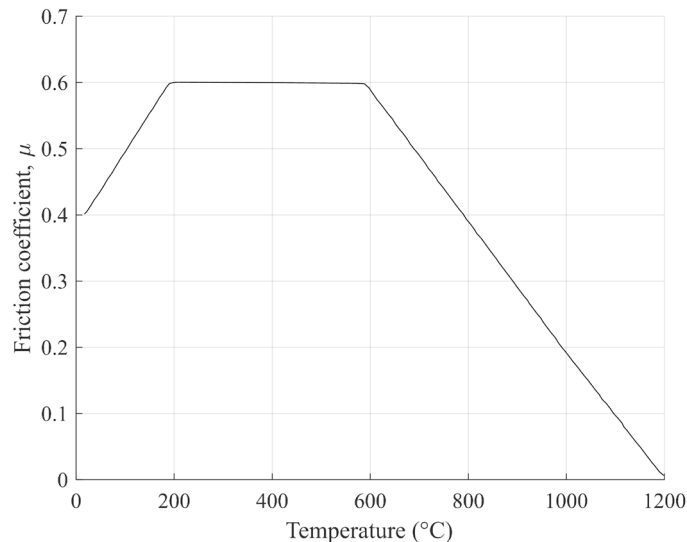


Fig. 3. Temperature-dependent friction coefficient, $\mu(T)$, for Ti-6Al-4V [8].

Simulations were conducted using a transient coupled time-displacement and fully coupled thermomechanical analysis. The latter needs the use of elements with both temperature and displacement degrees of freedom (DOF). Thus, in this work, CPS8RT (8-node biquadratic displacement, bilinear temperature, reduced integration) quad elements were employed from the ABAQUS library. Each part has 3945 nodes and 1352 elements. The initial temperature for both parts was predefined in ABAQUS at 27 °C representing room temperature.

The Oscillation Model (OM) has been used to simulate the four phases of the LFW process by several authors [4, 8, 7]. However, this approach is very time-consuming. A solution is to simulate each phase separately. The proposed Thermal Model (TM) focuses only on the heat generated by the friction in the initial phase. It replaces the dynamic thermal-structural simulation of the heat, generated by the oscillation, by an equivalent heat input (Eq. (2)) and

analyses the heat diffusion through the workpiece. Since 3D model requires significant computational resources, a 2D configuration was considered to assess the proposed methodology throughout the initial phase. In this way, the 2D model in-plane-stress condition represents a slice at the centre of a 3D model. The upper workpiece was constrained in x-displacement along the side faces of the parent material. In addition, the contact pressure was applied at the top of this part, and the gravity was not considered in both model. Moreover, the bottom face of the lower part was fixed in y-displacement. The heat flux coefficient at the edges surface of the HAZ and the TMAZ was set to -10W.m^{-2} as proposed by [2, 11]. Its negative sign represents the heat loss by the heat exchange between the HAZ and the ambient atmosphere.

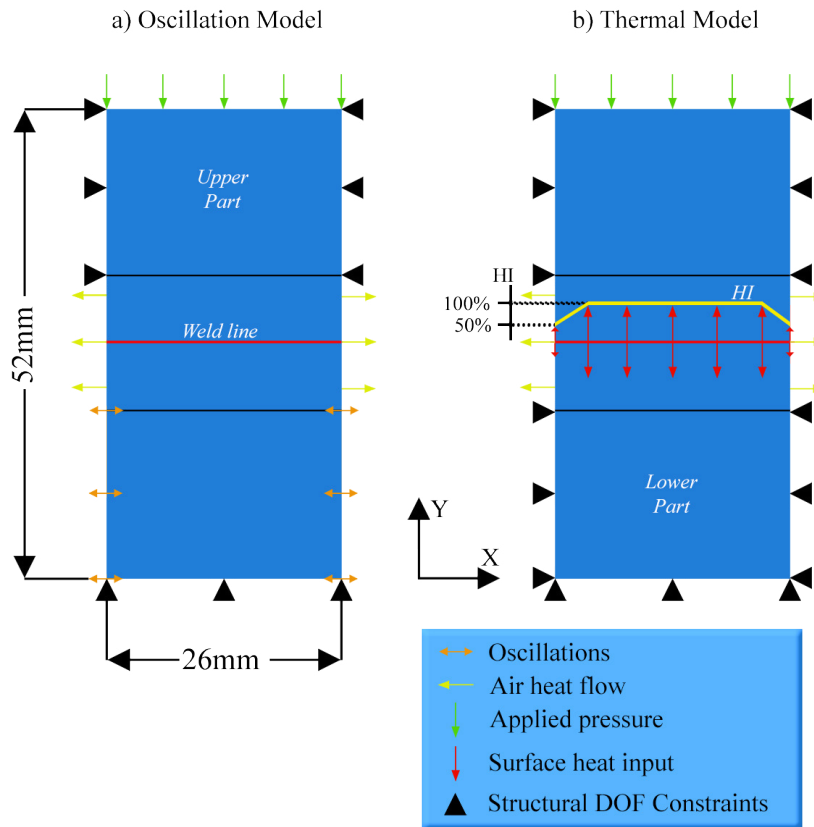


Fig. 4. Numerical model: a) oscillating model, b) heat transfer model.

3.1. Oscillating model

The four phases of the LFW process can be simulated when reciprocating motion is imposed. However, considering the oscillating movement of the workpiece increases the calculation time [3], the thermo-mechanical interactions are interdependent. Specifically, the temperature depends on the heat diffusion which depends on the heat flux at the weld interface. The latter depends on the friction work converted into heat which is a function of the temperature at the interface. In the present study, a time-dependent displacement was defined as a sinusoidal function $u(x)$ on the lower part along the two side faces of the parent material in the x -direction (Fig. 4.a):

$$u(x) = A \sin(2\pi ft).$$

Furthermore, the interface properties define a temperature-dependent friction coefficient (Fig. 3) according to the Coulomb's law. "Inelastic Heat Fraction" for the material and "Gap Heat Generation" are also defined, considering

that 90% of the friction energy [10] was converted to heat and used as a heat source: 50% of the frictional heat was assigned to each deformable part (i.e. equal heat distribution).

3.2. Thermal model

In the proposed model, the heat input replaces the friction interaction thereby simplifying the simulation: the heat released by the friction is instantaneously calculated and imposed. The simulation focuses on the heat diffusion and its conduction through the workpieces. The average heat input was determined using Fig. 3, in which the friction coefficient is temperature-dependent and then the calculated heat input at each time step was assigned at the interface using a user-defined subroutine (ABAQUS/DEFLUX). Non-Uniform heat flux was applied along the weld interface to compensate reciprocation movement of the lower part relative to the upper one in the thermal model. Indeed, the oscillating motion causes a portion of the lower and upper part (in an amplitude length) to experience more heat transfer with the environment thereby resulting in a slight decrease in temperature [2, 10, 11]. Therefore, it may be assumed that the heat flux distribution is linearly reduced from 100% to 50% along the weld interface over a length A (amplitude) from each side of the lower and upper parts, as shown in Fig. 4(b).

4. Results and discussion

In order to compare the proposed numerical methodology with the oscillation model, two processing parameters with LFW of the investigated alloy were used from the literature [12, 10]. Since LFW experiments had been performed by these parameters, the measured temperatures under these conditions were used to compare and validate the computed temperature results obtained from the two numerical methods. Furthermore, during the experiments, temperature evolution was recorded by thermocouples at various depths from the weld line. Interpolations were made to analyse the simulated temperature at the same location the thermocouples measured the temperature during the experiments. The values of the parameters (Simulation Parameters #1 & #2) used for thermal model and oscillation model simulations are listed in Table 2.

Table 2. LFW processing parameters obtained from Bühr et al. study [12] (Simulation Parameters #1) and McAndrew et al. study [10] (Simulation Parameters #2).

Welding Parameters	Simulation Parameters #1	Simulation Parameters #2
Frequency	50Hz	20Hz
Amplitude	2.7mm	1.5mm
Pressure	90MPa	125MPa

4.1. Temperature analysis

As can be seen in Figs. 5 and 6, the predicted temperatures of the thermal and oscillation models agree with experiments provided by Bühr et al. and McAndrew et al. studies [13, 15]. By using simulation parameter #1, the initial phase was completed in 0.82 s for both thermal and oscillation models. The temperature at 0.3 mm away from the weld line is 887 °C according to Bühr et al. [12]. The simulated temperature at the same point is 886 °C and 867°C for TM and OM, respectively.

The efficiency of the thermal model approach was also confirmed by employing simulation parameter #2. In this condition, the primary phase of LFW process lasted 4.7 s. It can be seen that the temperature at 0.3 mm far from the interface at the end of phase 1 for TM and OM simulations is 920 °C and 897 °C, respectively, for a measured temperature of 912 °C. These results are also in good agreement with the simulation results obtained with the simulation parameter #1.

The time required to complete the process decreases as the average surface heat input increases [2]. Considering the heat input equation (2) and the friction coefficient average value from Fig. 3, $\mu = 0.43$, the average heat input is 20.9 W.mm⁻² and 6.45 W.mm⁻² for simulation #1 and simulation #2, respectively. The findings correlate well with simulation #2 for which the initial phase takes 4.7 s while it takes 0.82 s for simulation #1.

A comparison between the predicted and measured temperatures for the thermal and oscillation models by using

simulation parameters #1 and #2 as well as their computational time are shown in Table 3 and Table 4. Thermal model results show a better agreement with the experimental values than that the oscillation one. The average absolute between the calculated and experimental temperatures along the TMAZ and HAZ in both thermal and oscillation models is 0.83% and 5.19%, respectively. Therefore, the proposed thermal model with a lowest average error is a suitable approach to simulate the initial phase of LFW process to optimise their processing parameters in phase 1.

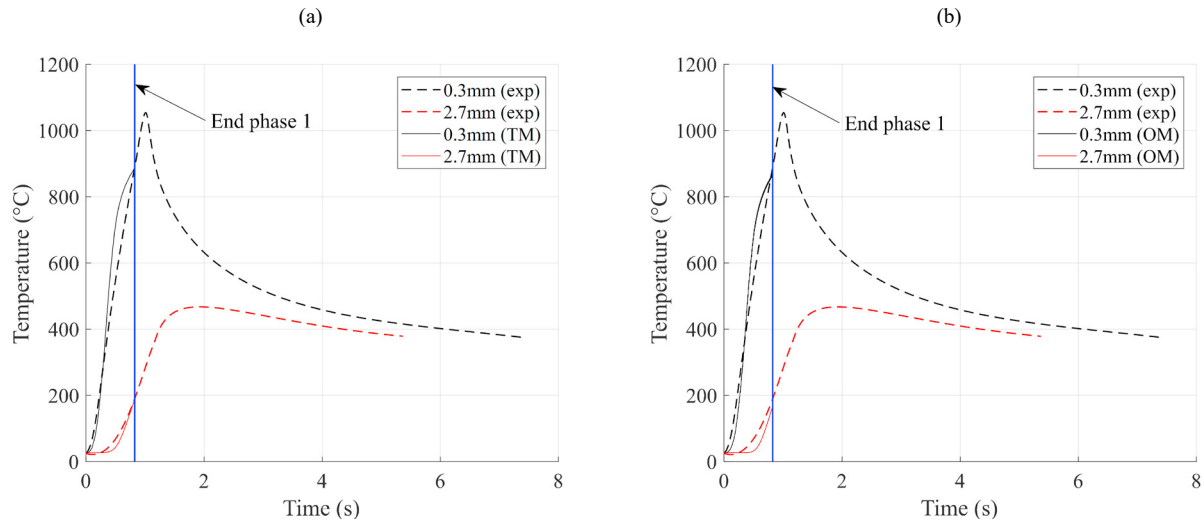


Fig. 5. Temperature history profile obtained under simulation parameters #1 at different distances from weld interface: (a) thermal model simulation (TM) results and (b) oscillation simulation (OM) results. The simulation results compared with experiments (exp) retrieved from Bühler et al. study [12].

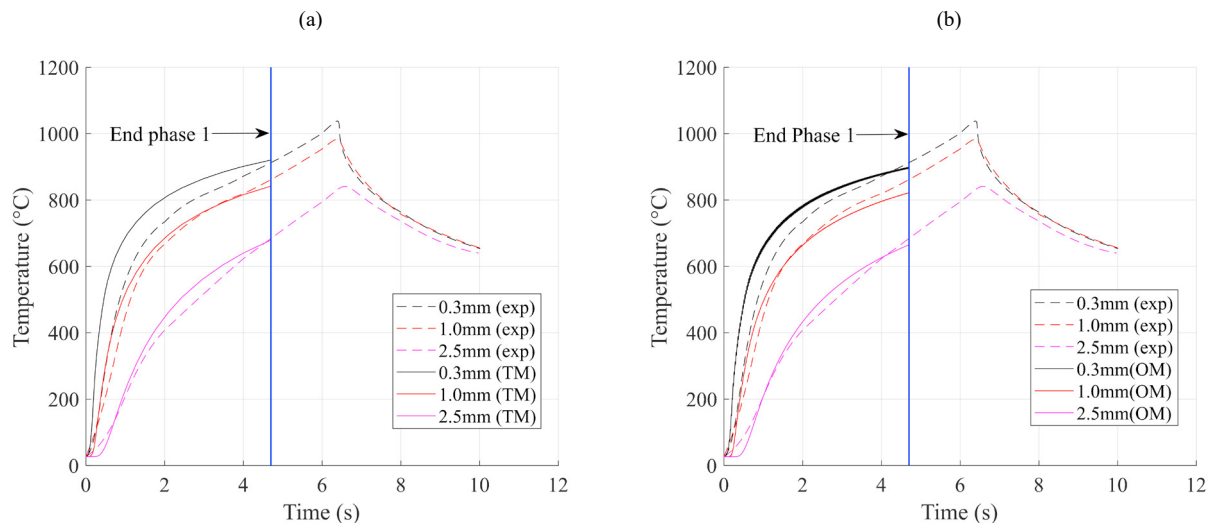


Fig. 6. Temperature history profile obtained under simulation parameters #2 at different distances from weld interface: (a) thermal model simulation (TM) results and (b) oscillation model simulation (OM) results. The simulation results compared with experiments (exp) retrieved from McAndrew et al. study [10].

Table 3. Error between predicted and measured temperatures [12] for both thermal & oscillation models by using simulation parameters #1.

Model	Thermal model	Oscillating model
0.3mm	- 0.0640%	- 2.22%
2.7mm	- 0.736%	-12.5%

Table 4. Error between predicted and measured temperatures [10] for both thermal & oscillation models by using simulation parameters #2.

Model	Thermal model	Oscillating model
0.3mm	- 0.864%	- 1.75%
1.0mm	- 2.25%	-4.54%
2.5mm	-0.663%	-2.76%

4.2. Computational time analysis

The Oscillation Model simulates the reciprocal motion and high plastic deformation. It requires appropriate time step increments to accurately calculate output variables, such as the heat generated by friction. Therefore, this model has a high computational cost and might lead to convergence issues (e.g. a tiny time-step increment can lead to numerical instability). Understanding heat input during LFW process initial phase is the key variable.

The heat flux occurring at the interface is calculated by the OM according to the reciprocal motion and the interface properties. Thus, the heat flux depends on the user-defined displacement function (3): it is a continuously variable function (e.g. sinusoidal), and the oscillation frequency defines the time step increments (i.e. higher is the frequency, smaller are the time step increments). The Thermal Model instead, uses a user-subroutine to calculate the heat flux. This subroutine defines a linear piecewise function which varies less than a sinusoidal function. Therefore, the time step increment for the TM can be longer than the one for the OM.

As a result, the time to complete the simulation will increase as the time step increment decreases (Table 5). The simulation #1 with the OM took 43min12s whereas it was 33s with the TM. The calculation time is much higher for simulation #2 as it took 1h47min to complete the simulation with the OM while it took only 39s to run it with the TM. It must be noted that, even though the TM does not consider the oscillation, the heat flux at the interface generated by the subroutine agrees with the heat flux generated by the OM. Furthermore, the temperature profile generated by the TM is close to the profile generated by the OM but with better accuracy, as previously mentioned. Finally, employing the average heat input (calculated from (2)) which can be applied by a subroutine in the thermal model reduced the computational time up to 99% with respect to the oscillating model.

Table 5. Computational cost analysis.

Simulation Parameters	Total Increments (TM)	Total Increments (OM)	Average Time Step Increment(TM)	Average Time Step Increment (OM)	Computational Time (TM)	Computational Time (OM)	Process Time Simulated
#1	24	1166	36ms \pm 40ms	0.71ms \pm 1.5ms	33s	2592s	0.82s
#2	30	3381	162ms \pm 385ms	1.39ms \pm 2.36ms	39s	6454s	4.7s

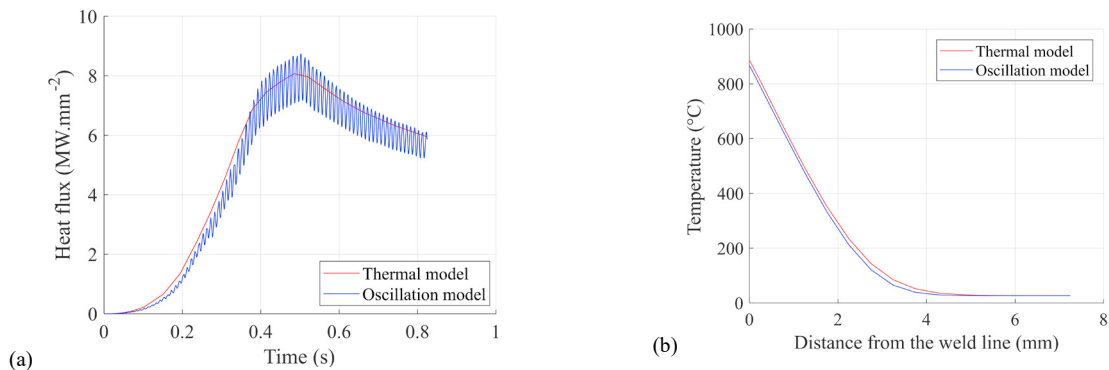


Fig. 7. Comparison between two models: (a) Simulated heat flux and (b) Temperature profile at mid-length of workpiece at end of initial phase by using simulation parameter #1.

5. Conclusions

This study provided a new numerical approach to simulate and optimise the initial phase parameters during LFW process. The following conclusions could be made:

- The computational time in the thermal model simulation is less than 99% the time used for the oscillation model simulation.
- The comparison between the published measured and calculated temperature profiles during phase 1 confirmed the accuracy of the proposed thermal model.

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