Dissolution of delta phase in Ni-based superalloy during linear friction welding: integrated multiphysics computational process modelling

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Abstract

Linear friction welding (LFW) is an increasingly popular solid-state joining method for challenging applications such as integrated blade disk of aero-engines. However, the influence of friction-generated heat on the material microstructural evolution, material deformation and resultant mechanical performance of the manufactured components is not well understood. A novel integrated multiphysics computational modelling is presented for predicting the component-scale microstructural evolution of IN718 alloy during LFW. A modified time-temperature equivalence formulation was implemented for predicting the evolution of the δ phase, which was coupled with thermomechanical modelling of the LFW process. There is reasonably good agreement between the computational modelling results of this paper and the experimental results from the literature in terms of δ phase volume fraction and weld temperature. The integrated multiphysics computational modelling predicts the influence of process parameters on thermomechanical and microstructural processes of IN718 LFW. By systematically analysing the influence of 10 different LFW process parameter configurations, the friction pressure was identified as the most influential process parameter determining the extent of δ phase dissolution and weld temperature during LFW.

Keywords Linear friction welding · Inconel 718 · Delta phase · Microstructural modelling · Time-temperature equivalence · Multiphysics modelling

Nomenclature

Acronyms and Greek

Al	Aluminium
BM	Base metal
DRX	Dynamic recrystallization
HV	Vickers Pyramid Number
IN718	Inconel 718
LFW	Linear friction welding
Nb	Niobium
Ni	Nickel

Ti	Titanium
TTE	Time-temperature equivalence
VUSDFLD	Abaqus/Explicit user-defined field subroutine
δ	Delta phase
ε	Plastic strain
$\dot{\varepsilon}$	Strain rate [1/s]
γ'	Gamma prime phase
γ''	Gamma double prime phase
μ	Friction coefficient
σ_s	Shear flow stress [MPa]
σ_y	Yield flow stress [MPa]
τ_{fr}	Frictional shear stress [MPa]

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Abbreviations

A_0	mm, Oscillating amplitude
$A(\varepsilon), n(\varepsilon)$	IN718 material constants
$\alpha(\varepsilon)$	
D_0	$\mu\text{m}^2\text{s}^{-1}$, Diffusion coefficient
f_0	Hz, Oscillating frequency
l	μm , Radius of γ matrix
L_a	mm, Axial shortening

Q	J.mol ⁻¹ , Activation energy for dissolution of δ phase
$Q(\varepsilon)$	J.mol ⁻¹ , Deformation activation energy
Q_{SPI}	Wm ⁻² , Specific heat input
p_f	MPa, Friction pressure
r	μm, Radius of δ phase
R	J.mol ⁻¹ K ⁻¹ , Gas constant
t	s, Time
T_{solid}	°C, Solidus temperature
T_{liq}	°C, Liquidus temperature
X	at. %, Atomic fraction (atomic per cent)

1 Introduction

Linear friction welding (LFW) is an energy-efficient, highly automated solid-state joining method that can produce high-quality welds by rapidly oscillating one workpiece relative to another under large compressive force. During LFW, friction heat is generated at the interface of two workpieces, which are in contact and in rapid relative motion [1, 2]. As the temperature of the material at the friction interface increases, it softens and is extruded as a flash in the direction of oscillation due to the continued compressive forces. Thus, flash formation is accompanied by an overall shortening of workpiece in the axis of applied force. LFW can avoid hot cracking that is often found in fusion welding [1, 2]. It is a self-cleaning process and does not use filler metal [1]. LFW can join similar and dissimilar alloys in varying geometric configurations [1–4]. It has been applied extensively for joining high-performance materials (e.g. nickel-based superalloys) with application in extreme environments (e.g. integrated blade disk of aero-engines). Despite the known benefits and applications of LFW, the influence of friction heat and friction force on the material microstructural evolution, material deformation and resultant mechanical performance of the manufactured components are still not well understood.

Nickel (Ni)-based superalloys are complex alloys that retain high strength, creep resistance and corrosion resistance at temperatures up to 1200 °C, which is about 90% of their melting points [1, 3, 5]. IN718 is a precipitation-strengthened Ni-based superalloy that has been widely used in varied LFW applications, including aero-engines, steam turbine power plants and nuclear power systems [3, 5, 6]. In IN718, γ'' (Ni₃Nb) and γ' (Ni₃Al) are the primary and secondary strengthening precipitates, respectively. The δ phase has the same composition as γ'' phase, precipitates at the grain boundaries and prevents grain boundary migration [7–9]. The microstructure of an alloy determines its material properties, as demonstrated via local hardness profiles around an IN718 LFW weld joint corresponding to local γ grain size and γ' volume fraction, size and distribution [10–13]. Ma et al. found

that the tensile strength and hardness of several IN718 weld joints were lower than the tensile strength and hardness of parent (non-welded) metal [13]. They identified rapid weld temperature variation and resultant conversion of γ' and γ'' phases to δ phase as factors responsible for the decreased mechanical properties of the weld. It was found that after multiple long-term exposures to high-temperature cycles, IN718 welds degrade and become difficult to repair by welding because of the accumulation of Nb-rich δ phase in grain boundaries and the depletion of δ phase in adjacent intergranular regions in the IN718 microstructure [14, 15]. Mary and Jahazi found that the loss of the δ phase in IN718 weld joint facilitates dynamic recrystallisation and dynamic recovery of γ grains in the weld joint during LFW [16].

The influence of thermomechanical process on the microstructural properties and mechanical behaviour of IN718 alloy has been reported in multiple studies. For instance, significant changes in the microstructure of γ' , γ'' and δ phases can occur on the friction interface of IN718 weld during LFW, in terms of volume fraction, size and spatial distribution [1, 10, 11]. These microstructural and resultant mechanical properties change when the friction interface is exposed to high temperature, high heating rate, high plastic strain and rapid cooling during LFW [1, 10, 11]. Roder et al. and Preuss et al. observed a 600-μm wide soft region on both sides of the friction interface of IN718 inertia friction welds where γ' , γ'' and δ phases are fully dissolved [17, 18]. This material softening, accompanied by dissolution of γ' , γ'' and δ phases on the friction interface, is beneficial for flash formation and improving weld integrity [17, 18]. Yang found that the rate of δ phase dissolution was affected by the heating rate while simulating microstructural evolution during thermomechanical processing of IN718 using Gleeble testing [10]. Other researchers agree with Yang that the heating rate as well as the size of γ' phase influence the rate of γ' phase dissolution in Astroloy and AD730 Ni-based superalloys [19–21]. In order to optimise the design of LFW process parameters, it is important to systematically and quantitatively analyse the influence of thermomechanical processes on the microstructural evolution of IN718, for example, the δ precipitate, during LFW process.

There are three key process parameters often considered for optimising the LFW process, which are friction pressure, oscillating frequency and oscillating amplitude. These key LFW process parameters have been experimentally varied at different levels, and their influence on temperature, heating rate and resultant microstructure and mechanical properties of IN718 weld have been reported [10–13, 22, 23]. Ma et al. found that the weld microstructure was significantly affected by high heat input resulting from increased friction pressure and amplitude [13]. They observed that dynamic recrystallization (DRX) and recovery were achieved by increasing the friction-generated heat. Similar results of enhanced DRX were reported by other researchers [24–26]. The temperature-

dependent yield strength of IN718 material has been reported to decrease with increasing friction pressure, leading to an increase in overall plastic strain and rate of flash formation at the friction interface [10, 11, 23]. Geng et al. pointed out that the flow velocity of materials at the friction interface increased when they increased oscillating frequency and oscillating amplitude during LFW of IN718 [22]. In another study, Qin et al. showed that increasing friction pressure resulted in increased value of maximum friction interface temperature during LFW [23]. Also, increasing oscillating frequency and oscillating amplitude resulted in increased values of maximum temperature and strain rate at the friction interface during LFW. Studies have noted that the regions of the friction interface without δ phase coincide with the regions where the temperature exceeds the solvus temperature of δ phase during LFW [1, 10, 11]. The microstructural evolution of γ' and δ phases has often been characterised by physically simulating LFW process using thermomechanical simulator testing [10, 19, 27, 28]. However, there are challenges in measuring the dissolution kinetics specifically in the supersolvus temperature range due to the rapidly varying volume fraction of precipitates [27].

While the temperature evolution of weld can be experimentally measured by using thermocouples, it can only be conducted at places of weld reasonably away from the friction interface [11, 24]. Moreover, the measurement of stress and strain and particularly their evolution during LFW process can be very challenging using experimental methods [1, 24]. Chamanfar et al. and Masoumi et al. reported that the local plastic deformation, strain and strain rate at the friction interface could not be directly measured by strain gauges due to the dynamic nature and overall configuration of LFW [1, 24]. Moreover, the dynamic evolution of material microstructure during LFW process is very difficult to characterise using experimental measurement. Computational modelling method is very good at predicting some dynamically evolving processes and phenomena, such as thermomechanical processes and material microstructural evolution during material processing. Extensive computational modelling research has been published on the thermomechanical processes of IN718 LFW [22, 23, 29–35]. However, there has been very little work published in relation to the computational modelling for the material microstructural evolution during IN718 LFW, especially relating to predicting the dissolution of δ phase during LFW.

The objective of this study is to develop an integrated multiphysics computational modelling for predicting the coupled thermomechanical-microstructural processes (at the component scale) during IN718 LFW. This modelling integrates the thermomechanical submodel with the microstructural submodel by using sequential coupling. It particularly predicts the dissolution process of δ phase during LFW.

2 Methods

A 2D computational modelling framework for LFW was developed within the general-purpose finite element solver ABAQUS and user-defined field subroutine (VUSDFLD) [36]. The integrated multiphysics computational modelling was developed by sequentially coupling a thermomechanical submodel for LFW process to a novel microstructural submodel for the δ phase dissolution of IN718 alloy. The 2D thermomechanical modelling reduces overall computation time and gives a reasonable representation of the LFW process.

2.1 Thermomechanical model

The thermomechanical model for LFW process was previously presented in a study by the authors [29]. In the thermomechanical modelling of this study, the two workpieces of the friction pair are both deformable. The elastoplastic deformation of workpieces, generation of friction heat at the friction interface and heat transfer of the workpieces are fully coupled in the thermomechanical model. The thermomechanical model was implemented by using the finite element Abaqus/Explicit solver, which is recommended for fully coupled thermal-mechanical problems and highly capable of resolving contact problems as well as overcoming excessive element distortion using dynamic remeshing [36].

2.1.1 Setup of thermomechanical modelling

In the computational modelling of this paper, the two workpieces—top and bottom—were discretized using the deformable plane strain formulation with elements defined in the

Fig. 1 Setup of the 2D thermomechanical model for LFW process with friction-paired deformable workpieces

X-Y plane and restricting deformation only to the defined plane. The two deformable workpieces shown in Fig. 1 have the same dimension of 33 mm by 14 mm. They are adjacent to each other, and there is an initial contact at the intended friction interface of workpieces. The workpiece dimensions employed in the computational modelling of this paper are same dimensions as the IN718 LFW experiments of Geng et al. and Qin et al. [11, 23]. Their study provided the experimental data utilised in this paper for model verification.

Element types of CPE4RT and CPE3T (4-node and 3-node thermally coupled, displacement and temperature, reduced integration, hourglass control) were specified on both workpieces. The thermomechanical modelling for the LFW process lasts for 5.0 s of welding time. Both workpieces use a similar mesh discretisation procedure involving two structured mesh zones and one unstructured mesh zone. There are 2454 elements and 2588 nodes for the entire model. Mesh refinement is specifically directed towards the friction interface and periphery of workpieces, where high temperature and high plastic strain are expected. Seeding was defined on the edges of the workpieces, only at the regions closest to the friction interface.

2.1.2 Constitutive material model and friction model

The elastic response of IN718 is assumed to be governed by Hooke's Law. Equations 1 and 2 denote the strain-compensated Arrhenius equation for the plastic material behaviour of IN718 alloy during LFW [22, 23, 31].

$$\sigma_y = \frac{1}{\alpha(\varepsilon)} \ln \left\{ \frac{Z(\varepsilon)}{A(\varepsilon)}^{1/n(\varepsilon)} + \left[\left[\frac{Z(\varepsilon)}{A(\varepsilon)}^{1/n(\varepsilon)} + 1 \right]^{2/n(\varepsilon)} \right]^{1/2} \right\} \quad (1)$$

$$Z(\varepsilon) = \dot{\varepsilon} \exp \left[\frac{Q(\varepsilon)}{RT} \right] \quad (2)$$

where σ_y is the yield flow stress, $\dot{\varepsilon}$ is the strain rate, T is the absolute temperature and R is the universal gas constant. $Q(\varepsilon)$ is the deformation activation energy; $\alpha(\varepsilon)$, $n(\varepsilon)$ and $A(\varepsilon)$ are material constants. They are respectively expressed as polynomial functions of deformation strain as:

$$\begin{aligned} A(\varepsilon) &= B_0 + B_1\varepsilon + B_2\varepsilon^2 + B_3\varepsilon^3 + B_4\varepsilon^4 + B_5\varepsilon^5 \\ n(\varepsilon) &= C_0 + C_1\varepsilon + C_2\varepsilon^2 + C_3\varepsilon^3 + C_4\varepsilon^4 + C_5\varepsilon^5 \\ Q(\varepsilon) &= D_0 + D_1\varepsilon + D_2\varepsilon^2 + D_3\varepsilon^3 + D_4\varepsilon^4 + D_5\varepsilon^5 \\ \ln A(\varepsilon) &= F_0 + F_1\varepsilon + F_2\varepsilon^2 + F_3\varepsilon^3 + F_4\varepsilon^4 + F_5\varepsilon^5 \end{aligned} \quad (3)$$

The coefficients of polynomial functions for the alloy material can be found in the research [30].

In this study, friction behaviour was represented by a plastically deformable friction pair. Contact between two

workpieces was formulated by using the 'surface-to-surface explicit' contact algorithm. The magnitude of contact pressure was computed in the thermomechanical modelling during LFW. Normal contact interaction was defined as hard (explicit default). Penalty tangential workpiece interaction, which related to the transmission of shear stresses across the contact interface, was defined via the friction coefficient [22, 37]. The friction coefficient depends on sliding velocity, friction interface temperature and contact pressure. This dependence can be expressed as:

$$\mu = f(p_f, v_s, T) \quad (4)$$

where p_f is the contact friction pressure, v_s is the sliding velocity and T is the interface temperature between the contacting friction surfaces. An exponential function has been previously employed for the target alloy IN718, in the form of a modified Coulomb friction law expressed as [31]:

$$\mu = ap_f^b T^c \exp(dv_s) \quad (5)$$

where the constants a , b , c and d are specified as 0.12, -0.233 , 0.471 and -0.739 , respectively [31]. Further, the maximum frictional shear stress τ_{fr} cannot be higher than the shear flow stress of IN718 material. Thus, once the maximum shear stress reaches a limit, the temperature and strain rate-dependent limited shear stress σ_s is implemented. This has been expressed by [23, 31]:

$$\tau_{fr} = \min \left(\mu p_n, \frac{\sigma_s}{\sqrt{3}} \right) \quad (6)$$

2.1.3 Initial and boundary conditions

Mechanical boundary conditions were defined on the stationary (top) workpiece as surface uniformly applied pressure,

Fig. 2 Results of mesh dependency testing

constrained x-axis displacement and unconstrained y-axis displacement (see Fig. 1). The oscillating (bottom) workpiece has x-axis sinusoidal displacement, while displacement is constrained in the y-axis. The x-axis sinusoidal displacement of the oscillating workpiece is controlled by:

$$x = A_0 \sin 2\pi f_0 t \quad (7)$$

where A_0 is the amplitude of oscillation (mm), f_0 is the frequency of oscillation (Hz) and t is the instantaneous weld time, from 0.0 to 5.0 s.

2.1.4 Dynamic remeshing and mesh dependency analysis

The arbitrary Lagrangian-Eulerian (ALE) adaptive meshing for automatic solution mapping was implemented to control excessive element distortion in the Abaqus/Explicit solver [36]. The mass-scaling algorithm was formulated at every analysis step in the Abaqus/Explicit solver. To ensure reasonable computational cost, a constant value of 800 was specified as the semi-automatic mass scaling objective definition at the beginning of each analysis step [36]. This semi-automatic mass scaling constant ensures that the kinematic energy is less than 5% of the internal energy [38]. A similar criterion for defining mass scaling factor has been recommended in other studies [30, 31, 39]. Three different partitions of mesh zones were defined for the thermomechanical model for LFW process. The partitions comprise of a structured fine mesh of element length 0.44 mm, an unstructured mesh zone of element lengths 0.44 to 1.64 mm (constant biasing of 0.3) and a structure mesh region of coarsened mesh size of length 1.64 mm (see Fig. 1). A mesh dependency analysis was conducted by using welding process parameters for one LFW setup (process parameter set J6, details below). Figure 2 shows the outcome of mesh dependency analysis whereby the calculated maximum friction interface temperature is insensitive to using higher number of elements, especially when using more than 2500 elements.

2.2 Microstructural model for δ phase

In this study, the δ phase dissolution during rapid heating process of LFW was formulated by employing a time-temperature equivalence (TTE) model [10, 19, 40]. The material properties of IN718 alloy and δ phase were sourced from Yang [10]. The equilibrium volume fraction of the δ phase is given as [10, 19]:

$$f_\delta(T) = \frac{X_{Nb} - X_{Nb,\gamma}(T)}{X_{Nb,\delta} - X_{Nb,\gamma}(T)} \quad (8)$$

where $f_\delta(T)$ is the volume fraction of δ at temperature T , X_{Nb} is the atomic fraction of Nb in the alloy, $X_{Nb,\gamma}(T)$ is the atomic fraction of Nb in the γ matrix at temperature T and $X_{Nb,\delta}$ is the

atomic fraction of Nb in the δ phase. The size and volume fraction of IN718 spherical δ phase prior to dissolution are $\sim 0.54 \mu\text{m}$ and 0.95%, respectively [10]. Equation 8 is based on the assumption that related phases are in thermodynamic equilibrium. During LFW process, however, the phases are not in thermodynamic equilibrium due to the high heating rate. Precipitate dissolution behaviour during rapid heating process differs from equilibrium dissolution [10, 19, 41]. In the TTE model, the thermal cycle with a heating rate V_h from the initial temperature T_0 at time t_0 to the maximum temperature T_p at time t_p and with cooling rate V_c (from T_p at t_p) to T_0 at t_f was replaced by an equivalent hold time t_e at maximum temperature T_p . The variable t_e is the sum of equivalent heating time t_{eh} and the equivalent cooling time t_{ec} , which may be expressed as [10, 19]:

$$t_e = t_{eh} + t_{ec} = \frac{RT_p^2}{Q} \left(\frac{1}{V_h} + \frac{1}{V_c} \right) \quad (9)$$

where R is gas constant and Q activation energy for dissolution of δ phase. The δ phase diffusive field extends a distance of $y = \sqrt{D_p t_e} + r$ into the γ matrix, where D_p is the diffusion coefficient of Nb in Ni that is associated with the maximum temperature and r is the radius of the spherical δ phase. Hence, the matrix volume fraction f_m that is affected by dissolution is expressed as [10, 19]:

$$y = \begin{cases} \sqrt{D_p t_e} + r < l & f_m = \frac{(\sqrt{D_p t_e} + r)^3}{l^3} \\ \sqrt{D_p t_e} + r > l & f_m = \frac{(\sqrt{D_p t_e} + r)^3}{(\sqrt{D_p t_e} + r)^3 + l^3} \end{cases} \quad (10)$$

The variation of the atomic fraction of Nb in the γ matrix $X_{Nb,\gamma}(T)$ is substituted by a variable $X_{Nb,\gamma}(T, t)$ related to the hold time t at temperature T , given as [19]:

$$X_{Nb,\gamma}(T, t) - X_{Nb,\gamma} = k \left((\sqrt{Dt} + r)^3 - r^3 \right) \quad (11)$$

where k is a constant that is independent of T and t , D is the diffusion coefficient of Nb in Ni at a specific temperature T and r is the radius of the δ phase. $X_{Nb,\gamma}$ is the atomic fraction of Nb in the γ matrix before δ dissolution. The variation of Nb concentration in the γ matrix around the precipitates is not considered. At the start of dissolution, $r = 0.54 \mu\text{m}$. At the temperature of complete δ dissolution T_c and equivalent hold time t_c during LFW process, $r = 0$. So k can be expressed as:

$$k = \frac{X_{Nb,\gamma}(T_c, t_c) - X_{Nb,\gamma}}{(\sqrt{D_c t_c} + r)^3} \quad (12)$$

Fig. 3 Flowchart of the integrated multiphysics computational modelling for LFW. The white coloured shapes represent the thermomechanical submodel, and the grey coloured shapes represent the microstructural submodel

The volume fraction of the δ phase in the rapid heating process of LFW is expressed as:

$$f_{\delta}(T) = \frac{X_{Nb} - X_{Nb,\gamma} - \left(\frac{X_{Nb,\gamma}(T_c, t_c) - X_{Nb,\gamma}}{(\sqrt{D_c t_c} + r)^3} \cdot ((\sqrt{D_p t_e} + r)^3 - r^3) \right)}{X_{Nb,\delta} - X_{Nb,\gamma} - \left(\frac{X_{Nb,\gamma}(T_c, t_c) - X_{Nb,\gamma}}{(\sqrt{D_c t_c} + r)^3} \cdot ((\sqrt{D_p t_e} + r)^3 - r^3) \right)} \quad (13)$$

where $X_{Nb,\gamma}$ is the atomic fraction of Nb in the γ phase before δ phase dissolution. The computation for phase fraction of δ phase using Equations 9, 10, 11, 12 and 13 was implemented by running computations using Abaqus/Explicit solver in conjunction with the authors' VUSDFLD subroutine. In the research by Yang, the TTE model analysis used three different levels of constant heating rate, such as 1 °C/s, 300 °C/s and 700 °C/s [10]. However, in the actual LFW process, heating rate is not a constant but a variable that varies during the welding process. In the integrated multiphysics computational modelling of LFW, the actual heating rate was calculated as:

$$V_h = \frac{T_n - T_{(n-1)}}{t_n - t_{(n-1)}} \quad (14)$$

where V_h is heating rate and T_n and $T_{(n-1)}$ are the current temperature at increment n and previous temperature at increment $(n-1)$ of thermomechanical modelling. The current time at increment n and the time at previous increment $(n-1)$ are represented using t_n and t_{n-1} . In this study, it was found that the heating rate could vary in the range of $0.01 \leq V_h \leq 903.4$ °C/s during the LFW process depending on the process parameters. In the microstructural modelling, it was assumed that the IN718 alloy had δ phase volume fraction of 0.95% before the start of LFW.

2.3 Model integration

The flowchart in Fig. 3 shows how the integrated multiphysics computational modelling works as well as the sequential

Table 1 Process parameters applied in LFW computational modelling

Number of weld	Friction pressure p_f (MPa)	Oscillating frequency f_o (Hz)	Oscillating amplitude A_o (mm)	Specific heat input Q_{SPI} (kW·m ⁻²)
J1	200	15	2.5	1193.7
J2	200	25	2.9	2307.7
J3	200	25	3.5	2785.2
J4	300	25	2.9	3461.6
J5	300	25	3.5	4177.8
J6	400	25	2.9	4615.5
J7	400	25	3.5	5570.4
J8	400	30	2.9	5538.6
J9	500	15	2.5	2984.2
J10	500	25	2.9	5769.4

Table 2 LFW input process parameters for thermomechanical modelling setup [23]

Input parameters of modelling		Material properties	
Heat partition coefficient	0.5	Density ρ (kg/m ³)	8420
Friction energy change to heat	0.9	Elastic modulus E (MPa)	221000
Mean friction coefficient	0.01–0.60	Poisson's ratio ν	0.3
Shear stress limit	60–100	Weld temperature T (°C)	25–1300
Welding process parameter		Conductivity λ (W/m/K)	$0.016T + 16.668$
Oscillating amplitude A_0 (mm)	2.5–3.5	Specific heat c_p (J/kg/K)	$0.33T + 452.09$
Oscillating frequency f_0 (Hz)	15–30	Expansion α_w (1/°C)	$4 \times 10^{-9}T + 10^{-5}$
Friction pressure p_f (MPa)	200–500	Inelastic heat fraction	0.9
Axial shortening L_a (mm)	1.0–7.5	Melting temperature (°C)	1300

coupling between the thermomechanical model and the microstructural model.

2.4 Process parameters of LFW and material properties

In total, 10 different process parameter sets for LFW were defined (see Table 1). They include friction pressure p_f , oscillating amplitude A_0 and oscillating frequency f_0 . These 10 different LFW setups were used as the background of computational modelling for systematically predicting the influence of process parameters on weld temperature and δ phase fraction of IN718 LFW. The specific heat input Q_{SPI} can be approximately estimated as [42]:

$$Q_{SPI} = \frac{p_f f_0 A_0}{2\pi} \quad (15)$$

The material properties of IN718 are assumed to be isotropic and homogeneous, with temperature-dependent material property data sourced from [23]. Other material properties and LFW input process parameters can be found in Table 2. Table 3 summarises the chemical composition of IN718 [5].

3 Results and discussion

3.1 Temperature evolution

Thermal history and maximum friction interface temperature are important indicators of the quality of LFWs in terms of desirable material microstructure and optimal mechanical properties. Figure 4 shows eight sampling points (A, B, C, D, E, F, G and H),

D, E, F, G and H) either on the friction interface or on the right side of the bottom workpiece at the start of welding (not drawn to scale). They are 2 mm apart before welding starts, although during welding, each point can get displaced further away from adjacent sampling points because of the deformation of the weld.

Figure 5 presents the computational modelling results of temperature at sampling points A, B, C and E (as shown in Fig. 4) for the LFW setup J6. There are four stages of LFW, including initial/contact stage, transition stage, equilibrium stage and extrusion/deceleration stage [1]. These stages occur at varying welding times depending on the configuration of

Fig. 4 Geometry of the bottom workpiece of LFW and the position of eight sampling points (A, B, C, D, E, F, G and H) identified on the friction interface and right side of the bottom workpiece in 2D

Table 3 Chemical composition of wrought IN718 in mass percentage [5]

Cr	Mo	Nb	Al	Ti	Fe	C	Ni
19	3	5.1	0.5	0.9	18.5	0.04	52.96

Fig. 5 Temperature histories of the bottom workpiece at sampling points A, B, C and E for LFW setup J6

welding process parameters and resultant material response during LFW [43, 44]. The initial stage is a brief stage at the start of LFW when workpieces first contact each other under friction pressure. In the transition stage, there is full surface contact with asperities, while the equilibrium stage indicates the absence of asperities and softening of friction interface material. Friction pressure is usually at maximum value during the extrusion/deceleration stage also accompanied by flash formation [2, 44].

In Fig. 5, the maximum temperature at sampling points A, B, C and E is 1301.2 °C, 1288.6 °C, 1072.4 °C and 870.2 °C, respectively. These maximum temperature levels are lower than the liquidus temperature of IN718 (~1360 °C) and were attained in the equilibrium stage of LFW. Sampling point A is shown to have the highest temperature; it is exactly at the mid-region of the friction interface. Sampling points B, C and E

show lower levels of temperature compared to sampling point A, and these three points are further away from the mid-region of the friction interface. The maximum temperature was reached at 3.2 s of welding for sampling points A, B and C, while the maximum temperature was reached at 5.0 s of welding for sampling point E. After reaching maximum temperature, the subsequent change in temperature value is $\pm 45^\circ\text{C}$ of the maximum temperature for sampling points A, B and C as shown in Fig. 5. Overall, after a process of very rapid increase in temperature, the weld temperature gradually evolves towards a plateau value during the equilibrium stage and extrusion stage of LFW.

Overall, the workpiece has the highest level of temperature near the centre of its friction interface and has lower level of temperature away from the centre of friction interface. Qin et al. and Okeke et al. have likewise identified varying temperature levels at different positions on the weld interface of this type [23, 29]. A similar phenomenon can be found for sampling points D, F, G and H. As the sampling points D, F, G and H are progressively spaced 2 mm from the friction interface, along the right side of the bottom workpiece, there is decreasing level of temperature.

The temperature contour for different friction times (between 1.0 and 5.0 s of LFW setup J6) can be found in Fig. 6. The figure shows a narrow area of high thermal gradient near the friction interface during the overall process of LFW. During LFW, the contacting workpieces rapidly rub against each other under large compressive force, thus transforming kinetic energy to thermal energy. Heat is generated at the weld interface and subsequently conducted to other places of the weld. This is very clear difference in the temperature field between 1.0 and 3.0 s of LFW (see Fig. 6). The change of temperature contour in the weld between 3.0 and 5.0 s is comparatively less pronounced and commonly described as

Fig. 6 Evolution of temperature field at the weld joint during LFW process for setup J6 where $p_r = 400\text{ MPa}$, $f_0 = 25\text{ Hz}$ and $A_0 = 2.9\text{ mm}$

Fig. 7 Evolution of Mises stress at the weld joint during LFW process for setup J6 where $p_f = 400$ MPa, $f_0 = 25$ Hz and $A_0 = 2.9$ mm

the quasi-steady-state behaviour of IN718 during LFW [23, 32]. Considerable thermal softening of material near the friction interface can be seen between friction time of 3.0 s and 5.0 s, as shown in Fig. 6. Flash formation and axial shortening of the weld happened, while the material near the friction interface got significantly heated and softened by friction heat.

3.2 Mises stress and plastic strain fields

Figures 7 and 8 show the modelling results of von Mises stress and equivalent plastic strain and their evolution with time during LFW process for setup J6. At 1.0 s of welding, the maximum Mises stress is 1592 MPa, and the equivalent plastic strain is 6.04. At 2.0 s of welding, no significant deformation of material occurs yet, and maximum Mises stress and plastic strain are 1611 MPa and 7.32, respectively. Up to 3.0 s of welding time, the maximum Mises stress reduces to 421

MPa, and the maximum plastic strain increases to 7.37. This decrease in maximum stress during LFW refers to the quasi-steady-state behaviour of IN718, whereby increasing temperature at the friction interface does not increase the Mises stress field [23, 32]. The overall plastic deformation at the interface is initially driven by friction heat, which is later replaced by plastic work as the driving force of plastic deformation at thermal equilibrium [22, 23]. Based on this computational modelling result, it can be concluded that this stage of thermal equilibrium happens at welding time of 3.2 to 4.5 s for LFW setup J6. The extrusion stage of welding (between 4.0 and 5.0 s) shows a maximum plastic strain (~ 7.37) on the periphery of the friction interface for the top and bottom workpieces. Shearing and extrusion are the two principal modes of deformation influencing the stress and strain distribution during LFW of IN718 [22, 23, 32].

Fig. 8 Evolution of equivalent plastic strain during LFW process for setup J6 where $p_f = 400$ MPa, $f_0 = 25$ Hz and $A_0 = 2.9$ mm

Fig. 9 Comparison of experimentally measured results of temperature (experiment) of Qin et al. and computational modelling results of temperature (modelling) for LFW setups J2, J4, J6 and J10 [23]

3.3 Verification of thermomechanical modelling

3.3.1 Temperature history

The modelling results of temperature for LFW setups J2, J4, J6 and J10 (see Table 1) were compared with the result of experimental measurements by Qin et al. for the same alloy and the same setup of LFW process [23]. The modelling results of temperature were sampled at 5 mm away from the friction interface, which was how Qin et al. measured the temperature evolution of their welds during LFW using thermocouples [23]. As can be found in Fig. 9, the modelling results of temperature agree well with corresponding results of experimental measurement of Qin et al.

Fig. 10 Comparison of computational modelling results of axial shortening (modelling) with experimentally measured results (experiment) of Qin et al. for LFW time of 5.0 s based on setups J2, J4, J6 and J10 [23]

Fig. 11 Evolution of δ phase volume fraction of the bottom workpiece sampling points A, B, C and E for LFW setup J6

3.3.2 Macrostructural features: flash shape and axial shortening

Flash formation and axial (y -axis) shortening are important indicators of LFW weld integrity. Geng et al. measured the axial shortening of LFW setups J2, J4, J6, J8 and J10 as 1.6 ± 0.2 mm, 2.3 ± 0.3 mm, 4.8 ± 0.2 mm, 5.1 ± 0.3 mm and 6.8 ± 0.4 mm, respectively [11]. The computational modelling results of axial shortening by the authors are 1.18 mm, 1.72 mm, 3.84 mm, 6.32 mm and 7.84 mm for setups J2, J4, J6, J8 and J10, respectively. As shown in Fig. 10, the modelling results of axial shortening agree well with corresponding experimental results of Qin et al. [23]. Flash formation has self-cleaning effect, and axial shortening can improve joint integrity [11, 45]. A critical axial shortening of $l_a \geq (4.8 \pm 2)$ mm was

Fig. 12 Evolution of δ phase volume fraction with temperature at sampling points A, B, C and E during the LFW process corresponding to setup J6

recommended by Geng et al. to achieve a sound joint free of oxides at the interface [11]. In the current study, LFW setups J6 and J10 indicated axial shortening of 6.3 mm and 7.5 mm, respectively, thus satisfying the recommended critical axial shortening. Comprehensive modelling results of the thermomechanical processes of LFW can be found in a paper previously published by the authors [29]. The thermomechanical modelling results are only briefly presented in this paper in order to facilitate the analysis of the influence of thermomechanical process on material microstructural evolution during LFW.

3.4 Microstructural evolution of weld and model verification

Figure 11 shows the computational modelling results of temporal evolution of δ phase volume fraction at sampling points A, B, C and E. δ phase volume fraction is 0.95% between welding time of 0.0 s and 1.0 s at all four sampling points. There is no δ phase dissolution at welding time of 1.0 s yet because the temperature at 1.0 s is below the δ phase equilibrium solvus temperature of 1010 °C (see Fig. 5). The δ phase volume fraction starts decreasing at welding time of 1.6 s, 2.1 s and 3.1 s for sampling points A, B and C, respectively. δ phase dissolved completely at welding time of 2.3 s, 2.6 s and 3.5 s for sampling points A, B and C, respectively. Thus, the dissolution rate is higher for sampling points near the mid-region of the friction interface than for sampling points further away from the mid-region of friction interface. The δ phase

Fig. 13 Comparison of experimentally measured results of δ phase volume fraction (experiment) of Yang and microstructural modelling results of δ phase fraction (modelling) by the authors at sampling point A (on the friction interface) during LFW process of setup J6. The experimental results of Yang are for three different levels of constant heating rate of 1 °C/s, 300 °C/s and 700 °C/s, while the modelling results are grouped into five different bands of heating rate, which include 0.01 to 349 °C/s, 350 to 499 °C/s, 500 to 649 °C/s, 650 to 799 °C/s and 800 to 904 °C/s [10]

Fig. 14 Comparison of experimentally measured results of δ phase volume fraction (experiment) of Yang and microstructural modelling results of δ phase fraction (modelling) by the authors at sampling point A (on the friction interface) during LFW process of setup J8. The experimental results of Yang are for three different levels of constant heating rate of 1 °C/s, 300 °C/s and 700 °C/s, while the modelling results are grouped into five different bands of heating rate, which include 0.01 to 349 °C/s, 350 to 499 °C/s, 500 to 649 °C/s, 650 to 799 °C/s and 800 to 904 °C/s [10]

volume fraction of sampling point E did not change during LFW, indicating that the maximum temperature for point E did not reach the δ phase equilibrium solvus temperature of 1010 °C. The δ phase volume fraction remained 0.95% during LFW for all sampling points positioned on the right-hand side of the bottom workpiece.

Figure 12 shows the microstructural modelling results of the evolution of δ phase volume fraction with temperature at four sampling points (A, B, C and E) for setup J6 during LFW process. It can be seen that the δ phase volume fraction decreases nonlinearly with increasing temperature for sampling points A and B. δ phase completely dissolves at the temperature between 1182 and 1223 °C. Sampling point C shows partial δ phase dissolution up to 1070 °C. No δ phase dissolution occurred at sampling point E because the maximum temperature at point E is 903.2 °C, which is considerably below 1010 °C (δ phase equilibrium solvus temperature). The equilibrium dissolution of δ phase starts at ~1010 °C and completes at ~1070 °C [10]. However, the actual solvus temperature can be higher than 1070 °C for a rapid continuous heating process like LFW, thereby shifting the δ phase dissolution to a higher level of temperature as heating rate increases, as found in multiple studies [10, 19, 20].

The microstructural modelling of δ phase—in terms of volume fraction and spatial distribution—can be verified by comparing the microstructural modelling results with related experimental results of Yang [10]. The microstructural modelling of δ phase volume fraction was completed for LFW setups J6 and J8, and the computational results of evolution

of δ phase volume fraction with temperature at sampling points A are displayed in Figs. 13 and 14. In Figs. 13 and 14, experimental results of Yang for δ phase volume fraction are presented at three different levels of constant heating rate including of 1 °C/s, 300 °C/s and 700 °C/s, and their respective δ phase solvus temperature values are 1090 °C, 1182 °C and 1200 °C [10]. In the experimental research of Yang, Gleeble testing of IN718 alloy was completed at the related three different levels of constant heating rate [10]. In the practical LFW and in the thermomechanical modelling of LFW, the heating rate of weld is a variable that can vary significantly and continuously vary during LFW process, for example, as shown in Fig. 5. In the integrated computational modelling, the heating rate is computed by the thermomechanical submodel and used as one of the inputs of the microstructural submodel for computing the δ phase fraction. In order to compare the modelling results of δ phase volume fraction with the Gleeble testing results of Yang [10], the microstructural modelling results of δ phase volume fraction of this paper were grouped into different bands of heating rate such as 0.01 to 349 °C/s and 350 to 449 °C/s as shown in Figs. 13 and 14. It can be seen that the microstructural modelling results of δ phase volume fraction agree well with corresponding experimental results by Yang [10].

Besides verifying the integrated multiphysics computational modelling, the modelling results shown in Figs. 13 and 14 can clearly show the influence of process parameters on δ phase evolution in the weld during LFW. Setup J8 uses higher level of energy input compared to setup J6 (see Table 1). It can be seen that in Fig. 13 (Setup J6), the scattered symbols representing modelling results of δ phase volume fraction mainly fall in the high heating rate bands (350 °C/s and above). In Fig. 14 (Setup J8), however, many data points of the modelling results of δ phase volume fraction fall in the low

Fig. 15 Paths M–N and I–J–K–L, 10 mm and 34 mm long, respectively, at the surface of the bottom weld based on LFW setup J6

Fig. 16 Experimental results of profile of γ grain size and weld hardness of LFW-IN718 of Geng et al. and integrated multiphysics computational modelling results of temperature and δ phase volume fraction along path M–N based on LFW setup J6 at 5.0 s of welding [11]

heating rate band of 349 °C/s and below. This implies that δ phase evolution experiences a wider range of heating rate for high-energy input setup (Setup J8) compared to the δ phase evolution in a low-energy input setup (Setup J6).

3.5 Relationship between δ volume fraction, size of γ grain and microhardness

In this section of the paper, the modelling results of δ volume fraction is analysed along path M–N (10 mm long) and path I–J–K–L (34 mm long) as shown in Fig. 15, at the surface of the bottom weld based on LFW setup J6. The length of path M–N can get significantly reduced, and the length of path I–J–K–L can get significantly increased because of axial shortening and flash formation of weld during LFW process as shown in Fig.

Fig. 17 Experimental result of profile of γ grain size of LFW-IN718 of Geng et al. and computational modelling results of profile of temperature and plastic strain along a sampling path M–N based on LFW setup J6 at 5.0 s of welding [11]

15. In this paper, the direction of path M–N is always from M to N, and the direction of path I–J–K–L is always from I to J, J to K and K to L. The path I–J–K–L is not separated but a continuous path identified on the bottom workpiece.

As shown in Fig. 16, the profile of δ phase volume fraction, temperature, size of γ grain and microhardness of weld is analysed along path M–N of the bottom workpiece for LFW setup J6 at 5.0 s of welding. The profile of δ phase volume fraction and temperature is a result of the integrated computational modelling of this paper. The profile of γ grain size and microhardness of weld is an experimental result of Geng et al. for IN718 LFW using the setup J6 [11]. Overall, the δ phase volume fraction increases from the friction interface towards the base metal (BM), which is about 3.5 mm relative to the friction interface, along the path M–N. The increase in δ phase volume fraction is due to the decreasing temperature away from the friction interface towards the BM. By related experimental results of Geng et al., the weld hardness decreases from a maximum value of 295 (at the friction interface) to a minimum value of 270 HV (1 mm away from the friction interface) [11]. Geng et al. identified the lowest value of weld hardness in the thermomechanically affected zone (TMAZ) and attributed the weld hardness profile to the combined influence of DRX and dissolution of strengthening phases [11]. The high level of material hardness at the friction interface is related to the refined γ grains due to DRX.

In Fig. 17, the profile of γ grain size, temperature and plastic strain is analysed along path M–N of the bottom workpiece for LFW setup J6 at 5.0 s of welding. The profile of γ grain size is the experimental result by Geng et al., and the profile of temperature and plastic strain is the result of the integrated multiphysics computational modelling of this paper [11]. At the friction interface, as shown in Fig. 17, there is very high level of temperature and strain. They facilitate significant DRX of γ grains at the friction interface. The refined γ grains result in high level of hardness at the friction interface. The γ grain size increases with decreasing temperature and decreasing plastic strain towards the BM and reaches the BM value (the BM is 3.5 mm relative to friction interface and beyond). This finding is consistent with the experimental results of Mary and Jahazi that grain size measurements at distances greater than 3.0 mm from the friction interface remained constant and equal to that of the BM value [16].

The relationships between the integrated multiphysics computational modelling results of this paper and experimentally measured results from literature give some insight into the extent to which the LFW process can induce significant microstructural evolution in the IN718 welds. For example, the overall results presented in Figs. 16 and 17 illustrate how high temperature and high strain can induce DRX and δ phase dissolution, resulting to varying profiles of γ grain size and hardness on the surface of the IN718 weld. DRX, dynamic recovery and dynamic phase dissolution are recognised

mechanisms of microstructural evolution resulting from high temperature and high strain at the weld during LFW of IN718 [10, 11, 46]. Yang attributed the uneven hardness of IN718 welds to dissolution of strengthening phases during LFW [10]. However, Geng et al. found that dissolution of strengthening phases of IN718 is a secondary contributor to the increased hardness and decreased γ grain size at the IN718 weld joint; DRX is primarily responsible for the increased hardness at the IN718 weld joint [11]. The integrated multiphysics computational modelling of this paper has shown through process-structure prediction capability that it can be used to predict and/or interpret how related thermomechanical processes can affect the material microstructure of LFW weld.

3.6 Influence of LFW process parameters on properties of weld

Figure 18 shows profile of temperature (identified with subscript ‘T’) and δ phase fraction (identified with subscript ‘p’) for each of paths I–J, J–K and K–L for LFW setup J6 at 5.0 s of welding. Although paths I–J, J–K and K–L have been separately identified using subscripts, the direction of path I–J–K–L is always from I to J, J to K and K to L. Each of paths I–J, J–K and K–L elongates during LFW because of weld deformation. In the Cartesian coordinate system of the 2D modelling of this paper, the centre of friction interface of the bottom workpiece is at $x = 0$. The profiles of δ phase fraction along paths I–J and K–L show that no δ dissolution occurred at the side surface of weld because the maximum temperature (872.488 °C) is considerably below the δ phase equilibrium solvus temperature (1010 °C). However, δ phase fraction profile along path J–K shows fully dissolved, partially dissolved and undissolved δ phase regions at $x = 5$ mm, 6 mm and 7 mm, respectively, relative to the centre of friction interface. The

Fig. 18 Computational modelling results of profile of temperature and δ phase volume fraction along paths I–J, J–K and K–L for LFW setup J6, with subscript ‘T’ for temperature and subscript ‘p’ for phase fraction

corresponding temperature profile of path J–K shows that in the fully dissolved, partially dissolved and undissolved δ phase regions, weld temperature is approximately 1231.89 °C, 1067.51 °C and 844.612 °C, respectively. Thus, δ phase tends to dissolve in regions of very high temperature level.

Figure 19 a to d illustrate the profiles of δ phase volume fraction and temperature along the path I–J–K–L (see Fig. 15) at 5.0 s of welding for all 10 different LFW setups. In Fig. 19, in order to improve the visibility of respective curves, the profiles along path I–J–K–L are presented by using continuous lines without identifying the points I, J, K and L.

Figure 19a shows that δ phase did not dissolve during LFW process of setup J1, because the temperature of weld is well below the δ phase equilibrium solvus temperature (1010 °C). For LFW setups J2 and J3, δ phase is fully dissolved at the friction interface between its centre and $x = 5$ mm and $x = 6$ mm, respectively, along the path I–J–K–L. In these regions of path I–J–K–L where δ phase has been fully dissolved, the temperature is higher than the δ phase equilibrium solvus temperature. The maximum temperature of setup J3 (1460 °C) is higher than that of J2 (1440 °C).

LFW setup J5 shows (in Fig. 19b) considerably higher temperature (maximum temperature of 1430.54 °C) than the liquidus temperature of IN718 because of the higher level of oscillating amplitude employed. Similar results were found in the research [29]. For high friction pressure welding of IN718 (300 to 500 MPa), increasing the oscillating amplitude above 2.9 mm can result in extremely high weld temperature and excessive flash formation, because the rubbing velocity increases even at the same level of oscillating frequency of 25 Hz [22, 23, 30, 47]. The maximum temperature of LFW setups J4 (1292.88 °C) and J6 (1297.10 °C) is slightly above the solidus temperature (1250 °C) of IN718 alloy. For LFW setup J4, J5 and J6, δ phase is fully dissolved at the friction interface up to 5 mm, 6 mm and 7 mm, respectively, relative to its centre.

In Fig. 19c, δ phase did not dissolve for LFW setup J9 because the maximum temperature for J9 (658.54 °C) is below the δ phase equilibrium solvus temperature. For LFW setup J7, J8 and J10 shown in Fig. 19 c and d, the δ phase is fully dissolved at the friction interface up to 3 mm, 6 mm and 4 mm, respectively, relative to its centre.

Fig. 19 Computational modelling results of profile of temperature and δ phase volume fraction along the path I–J–K–L for LFW setups **a** J1, J2 and J3; **b** J4, J5 and J6; **c** J7, J8 and J9; and **d** J7, J8 and J10

The results shown in Fig. 19 a to d indicate that for different LFW setups, δ phase did not dissolve at the periphery of the bottom workpiece (such as approximately along paths I–J and K–L) because the temperature was relatively low. Temperature levels higher than the δ phase equilibrium solvus temperature were often observed near the centre of path J–K (on the friction interface). Figure 19 a to d show that, depending on the LFW process parameters, the path I–J–K–L can be elongated from an initial length of 34.0 mm up to the maximum length of 79.4 mm (like the LFW setup J7). The path is significantly elongated for friction amplitude $A_0 > 2.9$ mm, friction frequency $f_0 > 25$ Hz and specifically for higher friction pressure of $p_f > 300$ MPa (like the LFW setups J3, J5, J7 and J8). More importantly, the region of fully dissolved δ phase gets wider when applying higher levels of friction pressure, increasing from 200 to 500 MPa (like the LFW setups J2, J4, J6, J8 and J10). At the same level of friction pressure, for example, 400 MPa (like in LFW setups J6, J7 and J8), the region of fully dissolved δ phase is increased when higher values of oscillating frequency ($f_0 > 25$ Hz) and oscillating amplitude ($A_0 > 2.9$ mm) are employed.

Modelling results of setups J1 and J9 show that no δ phase dissolution took place during LFW. The reason is that the level of maximum temperature is 606.2 °C and 658.5 °C for setups J1 and J9, which is below the equilibrium solvus temperature of δ phase. Setups J1 and J9 have very low level of oscillating amplitude and oscillating frequency, which are 1.5 mm and 25 Hz, which result in too low level of energy input during LFW process. Other than setups J1 and J9, there is δ phase dissolution happening to some extents in all other LFW configurations along the path I–J–K–L (particularly at the friction interface) of weld. Partially dissolved phases can be observed between the temperature of 1015 °C and 1220 °C. No δ phase dissolution can be seen below the temperature of 1015 °C.

Along the path J–K, the average friction interface temperature and average δ phase volume fraction were analysed at 5.0 s of welding, and the results of analysis for all 10 different LFW setups can be found in Fig. 20. These average values were calculated by considering the temperature and δ phase volume fraction of all sampling points on path J–K (friction interface) of the bottom workpiece at 5.0 s of welding. Overall, for all 10 different LFW configurations, the average δ phase fraction is low when the average friction interface temperature is high. The highest and lowest average friction interface temperature were calculated as 1240.62 °C and 490.59 °C for setups J4 and J1, respectively. For all 10 different LFW setups, the values of average friction interface temperature are under 91% of the IN718 liquidus temperature, implying that no significant remelting occurred during LFW.

From the computational modelling results shown in Figs. 18, 19 and 20, it can be concluded that higher levels of friction pressure (≥ 200 MPa), oscillating frequency (≥ 25 Hz) and

Fig. 20 Computational modelling results of friction interface average temperature and average δ phase volume fraction at 5.0 s of welding for 10 different LFW setups

oscillating amplitude (≥ 2.9 mm) result in higher energy input (≥ 2307.7 kW·m⁻²), higher average friction interface temperature (≥ 1081.1 °C) and corresponding lower average δ phase volume fraction at the friction interface ($\leq 0.46\%$). Compared to oscillating frequency and oscillating amplitude, friction pressure has the most significant influence on maximum and average friction interface temperature and average δ phase volume fraction at the friction interface (like LFW setups J2, J4, J6, J8 and J10).

The integrated multiphysics computational modelling results have shown that amongst the LFW process parameters, friction pressure has the most significant influence on weld temperature and δ phase volume fraction, for example, at the friction interface of the weld. It was found by other researchers that the friction pressure dominates the weld zone characterised by significant δ phase dissolution and determines the size of the heat-affected zone (HAZ) [10, 12, 16, 42, 45]. In the study by Yang, the δ phase dissolution was noted to be more sensitive to the friction pressure and oscillating frequency than the oscillating amplitude [10]. In this study, δ phase at the friction interface can get completely dissolved during LFW process if its temperature can get sufficiently high.

4 Summary and conclusions

An integrated multiphysics computational modelling for LFW process was developed by sequentially coupling a thermomechanical model with microstructural model. This integrated multiphysics computational modelling considers mechanisms such as heat transfer, material elastic/plastic deformation and phase transformation. It is capable of computationally predicting the LFW process with regard to thermal history, stress/strain and δ phase evolution at the scale of the overall weld. It is the very first time ever that such an

integrated multiphysics computational modelling has been developed for LFW process of IN718.

Computational modelling was used to predict the influence of process parameters (such as pressure, frequency and amplitude) on temperature, strain and δ phase fraction of IN718 LFW welds by running computations corresponding to 10 different LFW setups. It was found that pressure has the most significant influence, while frequency and amplitude have less significant influence. High pressure results in high temperature and complete dissolution of δ phase at the friction interface of weld. Thus, this study demonstrates how the integrated multiphysics computational modelling can be used to systematically analyse the processes and optimise the process parameters for IN718 LFW. Besides completing related model verification, the modelling results were used to interpret related experimental results of other researchers in relation to why high material hardness and small grain size are commonly found at the friction interface of weld. Such modelling tools can enable the manufacturing industry to improve the design of LFW process parameters in a timely and cost-effective manner.

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Author contribution Saviour I. Okeke: conceptualization, data curation, formal analysis, investigation, methodology, software, verification, visualisation and writing—original draft.

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Declarations

Ethical approval Not applicable.

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