Thermomechanical modelling of the linear friction welding process for manufacturing high-performance fasteners

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ABSTRACT

This study investigates the linear friction welding (LFW) technique as a viable alternative to state-of-the-art bolt manufacturing technologies such as forging and machining. The research study details the three-dimensional (3D) thermomechanical finite element (FE) model for LFW of Inconel-718 nickel superalloy. This paper mainly presents the development of a reliable material constitutive model for Inconel-718 nickel-based superalloy, as well as improving functional relations and parameterization of the workpiece/workpiece contact-interaction model. The 3D FE model is used to predict thermo-mechanical response of Inconel-718 during welding. Temperature and displacement of the weld joint are examined as functions of the key LFW process parameters, such as oscillation frequency and oscillation amplitude. Qualitative validation of computational-analysis results showed good agreement with results of an experimental work that is available in open-domain literature.

Keywords: arbitrary Eulerian-Lagrangian, solid-state, Inconel-718, joining, linear friction welding

INTRODUCTION

High-performance heavy-duty bolts are often the limiting factors in structural components life, particularly offshore infrastructure, where hydrogen-induced bolt failures are common [1]. These bolts are produced by conventional bolt manufacturing processes such as machining and forging. Forging process involves high energy input, and can introduce undesirable microstructures in engineering components that lead to operational failures. Machining processes incur large material waste and high cost. Joining techniques that require powerful heat source are usually prone to hot cracking and often do not preserve the microstructure of the component material. In contrast, linear friction welding (LFW) is a low-energy, low-cost solid-state joining method widely used for the mass-production of high-quality weld joints, especially difficult-to-machine nickel-base alloy materials [3]. Friction welding is a solid-phase pressure welding process where the parent material
does not melt. The workpieces rub against each other during LFW process, which generates heat and forms local plastic zones at the weld interface.

High-performance friction-welded-bolts can potentially be less susceptible to hydrogen-induced failures that characterize the extreme offshore environment. However, the application of LFW process for the manufacture of nickel-alloy bolts has not been previously investigated, despite multiple experimental and numerical studies on the friction welding process in literature. Moreover, the thermomechanical process of the parent material during linear friction welding is not well understood, and such process has direct influence on the microstructure and mechanical properties of the weld [3, 5, 7].

The processes such as heat transfer and weld deformation during the friction joining process have been widely investigated by computational and experimental methods. A simplified two-dimensional (2D) finite element (FE) model that accounts for thermo-mechanical deformation in only one deformable workpiece was presented in references [4, 5, 7]. Sequentially-coupled thermal-stress analysis of the inertia friction welding process was investigated in Li et al. [2] and Yang et al. [6] where limited interaction was specified between thermal and stress analyses. In order to address the challenge of excessive element distortion during friction process simulation, the said authors developed python scripts that implement mesh mapping in the Abaqus/Standard solver. They used a dedicated particular software package Hyperworks to export the model geometry for challenging re-mesh procedures. McAndrew and colleagues [11] discussed the fully-coupled thermal-stress friction welding simulation for titanium-based alloy. Li et al. [2] and Grant et al. [13] developed a model of heat source for their 2D modelling of friction welding; however, these authors did not consider the full friction contact-interaction for heat generation in the modelling procedure. To date, there is very little work published on the three-dimensional (3D) computational modelling of fully-coupled thermo-mechanical deformation of two deformable workpieces during linear friction welding, for nickel-based superalloys.

The main contribution of this work is to develop a fully-coupled 3D thermo-mechanical model of the LFW process for Inconel-718 nickel-based superalloy at the macroscale, as well as investigate the influence of weld process parameters on heat transfer and weld deformation. The computational
modelling is used to parameterize and optimize the welding process parameters—oscillation frequency and oscillation amplitude.

**FINITE ELEMENT MODEL**

This section of the paper details the 3D FE model for linear friction welding (LFW) of Inconel-718 nickel-based superalloy. The fully-coupled thermo-mechanical model is implemented by using the Abaqus/Explicit solver. Abaqus/Explicit solver has capability for complex contact formulation and dynamic remeshing that are required in high-strain deformation thermomechanical analyses. Multiple published papers have developed either 2D or 3D models with one deformable and one rigid workpiece. The use of such an approach only provides partial insight of the thermo-mechanical analysis because deformation does not occur on the rigid workpiece. An important contribution of our work to the existing literature is to develop a friction-contact formulation for two deformable workpieces rubbing against each other. This treatment of two workpieces as deformable bodies depicts a complete thermo-mechanical interaction, and provides comparable results for two equally deforming workpieces.

There are four distinct phases identified in the LFW process [5, 6]: initial, transition, equilibrium, and forging phases. The present 3D model is mainly focused on the first three phases: the initial (contact) phase, the transition (friction) phase, and the equilibrium phase. These three LFW phases capture the welding process up to time of material softening and extrusion in the direction of reciprocation. The welding process involves the rapid conversion of kinetic energy to thermal energy at a frictional interface. Kinetic energy is derived from the oscillation of one workpiece relative to the other, in addition to frictional pressure applied to both workpieces.

In this numerical simulation, the two workpieces—the top workpiece for bolt head and bottom workpiece for bolt shaft—were discretized using the deformable plain strain formulation. The two deformable workpiece billets, as shown in figure 1, have dimensions of 40 mm by 20 mm by 20 mm. They are adjacent to each other and there is initial contact at the intended weld interface. Element type C3D8RT (8-node thermally coupled brick, trilinear displacement and temperature, reduced integration, hourglass control) was specified. The same multi-partition meshing strategy was applied to both workpieces. There are 5184 elements and 6442 nodes for the entire model. Mesh refinement is specifically directed along the friction interface and region where extreme friction
contact and high gradients of solution variables—temperature and displacement—are observed. Biased seeding is defined on the edges of the specimen at the regions closest to the weld line interface.

![Image of linear friction weld configuration for two workpieces. The images shown are the applied boundary conditions on the workpieces (left) and the meshing strategy for interacting workpieces (right).](image)

Figure 1. Linear friction weld configuration for two workpieces. The images shown are the applied boundary conditions on the workpieces (left) and the meshing strategy for interacting workpieces (right).

Table 1 summarizes the weight percentage chemical composition of Inconel-718 superalloy material [6]—a high-strength superalloy used in manufacturing heavy duty bolts. The elastic response of the material is assumed to be governed by the generalized Hooke’s Law.

<table>
<thead>
<tr>
<th>Cr</th>
<th>Mo</th>
<th>Nb</th>
<th>Al</th>
<th>Ti</th>
<th>Fe</th>
<th>C</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>19.00</td>
<td>3.00</td>
<td>5.10</td>
<td>0.50</td>
<td>0.90</td>
<td>18.50</td>
<td>0.04</td>
<td>52.96</td>
</tr>
</tbody>
</table>

Table 1. Weight percentage chemical composition of wrought Ni-base superalloy—Inconel 718 [6]

Thermophysical properties of IN-718 material [5, 6, 8] are presented in figure 2. The use of temperature-dependent coefficient of friction—to numerically account for heat generation during the welding process—is a dominant approach in literature [5, 6, 7, 10, 11]. Other material properties defined at room temperature (25 °C) are as follows: Young’s modulus 205 GPa, Poisson’s ratio 0.29, density 8220 kgm⁻³, coefficient of thermal expansion 12E06 m.m⁻¹°C⁻¹, and inelastic heat fraction 0.9.
Figure 2. Temperature-dependent material properties of Inconel-718 nickel-based superalloy [5, 6, 8]

Equation 1 shows the Johnson-Cook (JC) constitutive model of the plastic material behaviour during LFW process [4, 5, 10]. The equation is a non-linear relationship between flow stress \( \sigma \), effective plastic strain \( \varepsilon \), plastic strain rate \( \dot{\varepsilon} \), and temperature \( T \). The plastic response of the material is assumed to be strain hardenable, strain-rate sensitive, and thermally softenable. The JC model material constants are: \( A = 860 \) MPa, \( B = 1100 \) MPa, \( n = 0.5 \), \( m = 1.05 \), \( C = 0.0082 \), \( \dot{\varepsilon}_0 = 1 \), melting temperature, \( T_{melt} = 1300 ^\circ C \) and transition temperature, \( T_{room} = 25 ^\circ C \).

\[
\sigma = (A + B\varepsilon^n) \left[ 1 + C \ln \left( 1 + \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[ 1 - \left( \frac{T - T_{room}}{T_{melt} - T_{room}} \right)^m \right]
\]  

(1)

Mechanical boundary conditions are defined on the top workpiece as friction pressure and sinusoidal displacement, and on the bottom workpiece as fixed constraint. An average friction pressure of 285 MPa is applied to the top surface of upper workpiece; initial displacement of 0.2 mm is defined on the upper region of the top workpiece to enable smooth initiation of friction contact between both workpieces. The displacement is controlled by a sinusoidal relation \( x = A \sin 2\pi ft \) where \( A \) is the amplitude of oscillation (mm), \( f \) is the frequency of oscillation (Hz), and \( t \) is the instantaneous weld time, from 0 to 20 s. Thermal boundary conditions are mainly conductive and convective heat transfers. Radiation heat loss is assumed to be negligible. The workpiece billets are set to be at initial temperature of 25 °C (room temperature) [2, 5, 10]. For convective heat transfer, all surfaces have a heat transfer coefficient of 100 Wm\(^{-2}\) K\(^{-1}\). The heat generated at the interface is split equally between the two workpieces.
The contact formulation between workpieces is defined as the ‘general explicit’ contact algorithm. The magnitude of contact pressure is unlimited and automatically computed during the welding simulation process. Normal contact interaction is defined as hard (explicit default). Penalty tangential workpiece interaction—responsible for transmission of shear stresses across the contact interface—is modelled with the default Coulomb friction law in Abaqus/Explicit solver [5, 10]. This contact law expresses maximum shear stress as a product of contact pressure and static (before sliding) or kinetic (during sliding) friction coefficient. Temperature-dependent friction coefficient data are shown in figure 2. It is assumed that 95% of plastic deformation work is dissipated to the workpieces in the form of heat and the remaining 5% accounts for crystalline defects. Heat is equally partitioned to both top and bottom workpieces [5, 10].

During the computational modelling of the friction welding process, large strain values are obtained, which result in excessive distortion of the computational mesh, particularly in 3D computational modelling. The arbitrary Lagrangian-Eulerian (ALE) adaptive meshing is employed to implement automatic solution mapping, which controls excessive elements distortion [12]. Mass-scaling algorithm was formulated at every analysis step in the Abaqus/Explicit solver to ensure an accurate and stable simulation procedure with reasonable computational cost [12]. The computational analysis results obtained from the current numerical procedure were validated by qualitative comparison with experimental results published by Yang et al. [5] on the LFW process of Inconel-718 superalloy material.

RESULTS AND DISCUSSION
Parameterization and optimization of welding input process parameters
In this section, the results of the FE model are presented and discussed based on the temperature distributions for different cases (different values) of oscillation frequency and oscillation amplitude. The friction pressure values are the same for all investigated case studies. Figure 3 shows data curves for the optimal welding process input parameters. Multi-step plain strain analysis procedure was defined in Abaqus/Explicit as ‘dynamic, temperature-displacement explicit’.
Figure 3. Friction pressure, oscillation amplitude, and oscillation frequency data used for the friction weld simulation process in the current paper

Three different values of frequency—30 Hz, 45 Hz and 70 Hz—were specified for different LFW process simulations, while friction pressure (285 MPa) and oscillation amplitude (3.0 mm) remained constant. The process simulation for the smallest frequency, 30 Hz, indicated insufficient heat generation, low maximum temperature, and negligible axial shortening. Axial shortening is a measure of the difference in workpiece dimensions before and after friction welding process. The equilibrium phase of the welding process was not attained and the joining between the two workpieces was insufficient.

When frequency of oscillation was employed to be 70 Hz and other input parameters kept constant, a maximum temperature of 1700 °C—at weld process time of 1.0 s—was obtained, which exceeded the Inconel-718 liquidus temperature (1343 °C). The material became so hot and started to melt. The procedure was prematurely terminated as excessive mesh distortion created convergence difficulties, hence the incomplete curve shown for frequency of 70 Hz in figure 4. For the process simulation where frequency is 35 Hz, for 20 s of weld process time, optimal values of maximum temperature (1240 °C) and axial shortening (2 mm from weld interface) were successfully achieved; all phases of the friction welding process were attained. Figure 4 shows the temporal evolution of the maximum temperature of one workpiece during the LFW process at different levels of oscillation frequency.
In a separate set of case studies, the oscillation amplitude was employed to be at the respective levels of 1.0 mm, 3.0 mm, and 4.0 mm, while friction pressure (285 MPa) and oscillation frequency (45 Hz) remained constant. The temporal evolution of the maximum temperature of one workpiece during the LFW—at different levels of the oscillation amplitude—is shown in figure 5. At the oscillation amplitude of 1.0 mm, the maximum temperature at weld mid-joint interface was 500 °C during the overall 20 s of LFW. No significant deformation of the workpieces was observed. The weld interface was not hot enough to initiate material flow. The peripheral edges of the workpieces remained at 197 °C, after welding process completion, and did not show significant temperature increase during welding because of insufficient heat generation by the friction at this level of oscillation amplitude.

The simulation process at an amplitude level of 3.0 mm gave optimal results. Temperature at the weld interface increased very fast to 1100 °C, at weld time 0.5 s. The material started to flow at 2.0 s when maximum interface temperature reached 1220 °C. Maximum interface temperature was 1267 °C on completion of welding process at 20 s. For amplitude level of 4.0 mm, the interface elements were severely distorted due to extreme friction heat and excessive softening of the material. The simulation procedure discontinued at 1.5 s due to convergence failure. Within this weld time, temperature rapidly reached 1800 °C, which is well beyond Inconel-718 liquidus temperature.
Figure 5. Temporal evolution of the maximum temperature of one workpiece during the LFW process at different levels of oscillation amplitude during the LFW process.

The pressure strategy employed for all discussed case studies ensured that there were no severe temperature fluctuations during the multi-step welding process. Optimal input process parameters resulted in maximum temperature values below the melting point temperature; this is an important attribute of a sound weld with good mechanical properties.

**Temporal evolution and spatial distribution of weld interface temperature**

Temperature uniformity at contact interface and value of maximum interface temperature are pertinent factors to obtain sound weld with good mechanical properties. Figure 6 shows the temperature contour plots of one workpiece (bottom workpiece), at various stages during the LFW process. These results were obtained for optimal values of oscillation frequency and amplitude.
Temperature at local interface rises rapidly to 1150 °C between 0 s to 0.5 s during the welding process. The rapid frictional heat generation causes very quick heating of the parent material at the friction interface and generates a temperature gradient pointing from the friction weld interface towards the bulk of the workpieces. The friction heat is conducted away from the friction interface into the bulk of each deformable workpiece (figures 6(a)−(d)). At weld time of 1.0 s, the maximum temperature at the centre of the friction interface is 1132 °C. However, the peripheral edges have temperature of 763 °C due to periodic loss of contact between the faying surfaces. Other factors contributing to considerable temperature difference are: direction of reciprocation, reciprocating amplitude, and convective heat loss. There is no flash formation at weld time of 1.0 s. At weld time of 5.0 s, plastic work is observed in the gradual formation of flash at the weld interface (figure 6(b)). As the LFW progresses from 5.0 s to 20 s, the formation of flash becomes increasingly significant, which is characteristic of the quasi-steady state of the friction (transition) phase during the LFW process.

The maximum temperature of the workpiece reaches 1267 °C, at weld completion time of 20 s, which is well below the solidus temperature of Inconel-718 superalloy (1300 °C). The input welding process parameters ensure that the metal alloy begins to plasticise at temperatures where no undesirable microstructures are created. This condition is desirable to avoid the formation of brittle intermetallic phases. Indeed, LFW is a rapid process and the resultant microstructure within few seconds of joining two components could set the tone for the behaviour of the welded component (heavy duty bolt) under severe, complex operational conditions.
Temporal evolution, material extrusion and axial shortening

The LFW process is accompanied by material extrusion or flash formation. Flash is formed when material that was previously at the weld interface is heated, softened and expelled in the direction of oscillation during friction welding. Flash formation is beneficial for the expulsion of oxides and contaminants, and the creation of atomically clean weld joint with high bonding affinity. Figure 7 shows a typical result of the temporal evolution of flash during the equilibrium phase of the friction welding of Inconel-718 alloy.

![Figure 7. Evolution of the flash of weld during the LFW process. The contour represents local temperature at weld time of a) 5.0 s  b) 10.0 s  c) 15.0 s  d) 20.0 s](image)

As the metal layer softens and gets expelled, the workpieces reduce in height/thickness, a phenomenon referred to as axial shortening. Figure 8 shows the computational modelling result of axial shortening of the top workpiece compared to the axial shortening of the bottom workpiece. The curves show that there is approximately equal axial shortening of both workpieces, hence the deformation of weld is approximately equal.
Figure 8. A comparison of the axial shortening of the top workpiece and bottom workpiece at weld completion time of 20 s.

Qualitative comparison was conducted between our computational-analysis results and the experimental results published in Yang et al. [5] as shown in figure 9. In figure 9, the local interface temperature contour plots of the workpieces are shown for flash formation at various stages during the LFW process. All contour plots are presented in the X-Y view for clarity. The results of temperature evolution and flash formation in our work (figures 9(g) to 9(f)) were compared to the infrared thermal images (figures 9(a) to 9(c)) and high speed camera images (figures 9(d) to 9(f)) recorded in real time, as published by Yang and colleagues. The basis for comparison is that the material under consideration is the Inconel-718 nickel-based superalloy; the joining technique is similar as well as the condition of the welded component after completion of the LFW process. The results for optimal welding process input parameters in our work were used for the qualitative comparison with the experimental results from Yang et al.’s published work.

Considering the difference in the total weld process time between our work and Yang et al.’s work, the weld stage comparisons have been considered in three main weld periods. First, the same weld time of 1.0 s was considered for our results and Yang et al.’s results, as indicated in figures 9(a), 9(d), and 9(g) respectively. Second, the simulation progress half-way through the total welding time was compared in each study, that is 10 s in our work, but 1.5 s in Yang et al.’s work, as shown in figures 9(b), 9(e), and 9(f) respectively. Third, the temperature contours at weld completion time were compared; our weld completion time is 20 s while that of Yang et al. is 3.0 s as shown in figures 9(c), 9(f), and 9(g) respectively. Each contour plots above (Yang et al.’s results) is compared to the corresponding contour plots below (current results).
Figure 9. Temperature contour plots of flash formation at various stages of the LFW process. Infrared thermal images (a), (b), and (c) and the speed camera real time images (c), (d), and (e) from Yang et al. [5] are compared to temperature contour plots from our work (g), (h), and (f). Weld process times are: a) 1 s  b) 1.5 s  c) 3 s  d) 1 s e) 1.5 s f) 3.0 s g) 1 s h) 10 s i) 20 s.

Clearly, the results published by Yang and colleagues have emphasized the use of high-frequency and extremely high-speed LFW process for a short welding time of 3.0 s, compared to the current work that emphasized considerably high friction pressure for a longer LFW process time of 20 s. While our work has used different welding process parameters—oscillation frequency, oscillation amplitude, and friction pressure—from the work of Yang and colleagues, the overall computational-analysis results are in good agreement going by the qualitative comparisons presented. The 3D FE model implemented in our paper has been validated by the experimental results for the thermomechanical process of LFW of Inconel-718 nickel-based superalloy material that was presented in the work by Yang et al.
SUMMARY AND CONCLUSIONS
Computational modelling of the linear friction welding process for Inconel-718 was implemented in Abaqus/Explicit solver. The model is based on an arbitrary Lagrangian-Eulerian plain strain finite element formulation. It takes into account the important thermo-mechanical processes of the linear friction welding.

The friction welding process simulation showed the effect of key process parameters—oscillation amplitude and oscillation frequency—on the temporal evolution and spatial distribution of temperature and deformation fields on the weld. Optimal input process parameters are necessary to obtain high quality joint for the welded component. The predicted maximum temperature, flash formation, and axial shortening indicate that a sound weld with good mechanical properties was equally achieved for both workpieces during the LFW of Inconel-718 superalloy. These computational-analysis results have been validated by qualitative comparison with experimental results on LFW process of Inconel-718 superalloy material available in open-domain literature.

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