On the hot cracking susceptibility of a semisolid aluminium 6061 weld: Application of a coupled solidification-thermomechanical model

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Abstract. A coupled solidification-thermomechanical model is presented that investigates the hot tearing susceptibility of an aluminium 6061 semisolid weld. Two key phenomena are considered: excessive deformation of the semisolid weld, initiating a hot tear, and the ability of the semisolid weld to heal the hot tear by circulation of the molten metal. The model consists of two major modules: weld solidification and thermomechanical analysis. 1) By means of a multi-scale model of solidification, the microstructural evolution of the semisolid weld is simulated in 3D. The semisolid structure, which varies as a function of welding parameters, is composed of solidifying grains and a network of micro liquid channels. The weld solidification module is utilized to obtain the solidification shrinkage. The size of the micro liquid channels is used as an indicator to assess the healing ability of the semisolid weld. 2) Using the finite element method, the mechanical interaction between the weld pool and the base metal is simulated to capture the transient force field deforming the semisolid weld. Thermomechanical stresses and shrinkage stresses are both considered in the analysis; the solidification contractions are extracted from the weld solidification module and applied to the deformation simulation as boundary conditions. Such an analysis enables characterization of the potential for excessive deformation of the weld. The outputs of the model are used to study the effect of welding parameters including welding current and speed, and also welding constraint on the hot cracking susceptibility of an aluminium alloy 6061 semisolid weld.

1. Introduction

During fusion welding of aluminum alloys, cracks sometimes form and grow behind the weld pool, within the two-phase mushy zone, rupturing liquid films that are present at grain boundaries [1]. This phenomenon, known as hot tearing or hot cracking, is prevalent in both industrial casting and welding processes.

The mechanisms of hot tearing have been widely studied in casting processes (e.g. [2-11]). Two factors are frequently reported: 1) initiation of hot cracks by deformation of the mushy zone, and 2) healing of hot cracks by circulation of the molten metal within the mushy zone. Early studies by Pellini [4] and later Magnin et al. [5] showed that excessive deformation of the mushy zone in semisolid material arising from solidification shrinkage and thermal contraction serves to develop hot cracks. In addition, the formation of a hot crack is strongly linked to the grain morphology. The initiated mushy zone micro-cracks will only survive if the microstructural configuration does not allow for liquid feeding to heal the resulting defect [8, 9]. Vernède [2], and Sistaninia [12] have shown...
that the width of the micro liquid channels lying along the grain boundaries controls the healing ability of the mushy zone, where wider channels improve the healing process. The theory and knowledge of hot cracking in casting is also applicable to welding. As reviewed by Coniglio et al. [6], excessive tensile strain within a semisolid weld will lead to the formation of a hot crack. The role of the microstructure configuration on liquid feeding, and consequently hot cracking, is also extendable to welding [3]. Therefore, analyzing a semisolid weld in terms of deformation and microstructure can reveal insight into the susceptibility of the weld to this defect.

Due to the short lifetime of the semisolid weld and also the high temperature condition during welding, real-time experiments cannot be utilized to study the microstructural configuration of the mushy zone weld region and its healing ability, nor the deformations within the mushy zone. On the other hand, numerical techniques appear to be more feasible. Recently, some studies have been conducted to numerically reconstruct the microstructure of the semisolid weld at the meso scale. Zhong et al. [13] and Bordreuil et al. [14] have used cellular automaton (CA) method to reconstruct the 2-D microstructure of the semisolid weld. Zareie Rajani et al. [15] have also reconstructed the 3-D meso-scale microstructure of the semisolid weld composed of solidifying grains and micro liquid channels through a granular model of solidification. Unlike microstructural configuration, the deformation of the mushy zone during welding has not yet been examined using mathematical modeling at the meso scale. This is because of the challenges relating to simulating the complex force field deforming the semisolid weld [16, 17]. This transient force field acts on the interface between the base metal and the semisolid weld, i.e. the fusion surface, and evolves due to the thermomechanical response of the base metal to the solidification of the semisolid weld.

In this paper, a coupled thermomechanical-solidification model is presented to investigate the hot cracking susceptibility at the scale of the weld microstructure. The model consists of 1) a thermomechanical analysis module that determines the transient force field on the weld and then evaluates deformation of the mushy zone perpendicular to the weld line; and 2) a solidification module that reconstructs the microstructure of the mushy zone and yields part of the boundary conditions used in the thermomechanical analysis module. The model is applied to various welding scenarios to study the effect of welding parameters on formation of hot cracks during fusion welding of AA 6061.

2. Model description

2.1. Thermomechanical analysis module

The transient forces that act on the fusion surface and deform the semisolid during welding occur due to mechanical coupling between the base metal and the weld pool. The thermomechanical analysis module numerically solves the equation of conservation of momentum on the base metal of the weld to obtain the material flow within this domain caused by thermal stresses and solidification contraction during welding, and consequently to determine the reaction forces that evolve on the fusion surface, \( f_{\text{reaction}} \). Utilizing Newton’s third law of motion, the external force field acting on the semisolid weld during welding, i.e. \( f_{\text{fusion|semisolid weld}} \), is then calculated as:

\[
 f_{\partial \Omega_{\text{fusion|base metal}}} = -f_{\text{reaction}}
\]

In order to numerically solve the equation of conservation of momentum, the thermomechanical analysis module requires definition of a simulation domain with boundary conditions. The numerical solution to the transient stress analysis is then obtained using the commercial FEM solver ABAQUS.

2.1.1. Simulation domain

The simulation domain for the thermomechanical analysis consists of the base metal of the weld, and is shown in Figure 1. Due to symmetry, only one half of the base metal is simulated. The base metal is assumed to be a thin plate, and separated from its surroundings via a boundary (\( \partial \Omega \)) composed of
seven different surfaces: one parabolic fusion surface \((\partial \Omega_{\text{fusion}})\) representing the contact surface of the base metal and the weld line, one symmetry surface \((\partial \Omega_{\text{symmetry}})\) lying on the symmetry plane of the weld, four free surfaces \((\partial \Omega_{\text{free}})\) that are not in contact with anything but the air, and the back surface \((\partial \Omega_{\text{back}})\) that is assumed to be either free or constrained. Based on the defined Cartesian coordinate system, the depth and width of the plate respectively lie along the \(X\) and \(Y\) directions, and the \(Z\) direction follows the length of the plate and consequently the line of welding. The width and thickness of the base metal are assumed to be 50 mm and 3 mm, while the length of the domain is set at 20 mm. The simulation domain is then discretized through a nonuniform mesh composed of 8-node brick elements. The material properties are assumed to be elastic-thermoplastic with strain hardening, obeying the von Mises plasticity criterion. The relevant temperature-dependent flow stress curves for AA 6061 are shown in Figure 2 [18, 19]. ABAQUS obtains the temperature variation of flow stress of the base metal, \(\sigma_0\), through linear interpolation of the given flow stress functions for various temperatures.

![Figure 1. The simulation domain representing the base metal.](image1)

![Figure 2. Temperature-dependent flow stress curves for AA 6061.](image2)

### 2.1.2. Boundary conditions

For the boundary conditions, it is assumed that the four surfaces in contact with air have a homogenous boundary condition, \(\mathbf{f}|_{\partial \Omega_{\text{free}}} = 0\), where \(\mathbf{f}\) is the applied force. Dirichlet boundary conditions are applied to the remaining three surfaces. The symmetry surface is constrained in the \(Y\) direction due to the symmetry as well as the \(X\) and \(Z\) directions since the weld line is normally clamped during welding to prevent misalignment defects. On the back surface, different displacement Dirichlet boundary conditions can be applied, i.e. \(\mathbf{U}|_{\partial \Omega_{\text{back}}} = \mathbf{U}_0\) where \(\mathbf{U}_0\) is the imposed displacement, to model various welding constraints including clamping \((\mathbf{U}_0 = 0)\), and application of tension/compression \((\mathbf{U}_0 \neq 0)\). It is also possible to assume that the base metal is not clamped during welding by setting a homogenous boundary condition for the back surface. The Dirichlet boundary condition applied to the fusion surface, i.e. \(\mathbf{U}|_{\partial \Omega_{\text{fusion}}}) = \mathbf{D}(\mathbf{x}, t)\), is the most complex since the displacement field on the fusion surface, \(\mathbf{D}(\mathbf{x}, t)\), is imposed by nonuniform solidification of the semisolid weld rather than a mechanical tool. This boundary condition can be obtained by performing a meso-scale solidification simulation within the weld pool.

### 2.2. Solidification module

The solidification module determines the displacement field on the fusion surface, and completes the boundary conditions needed by the thermomechanical analysis module. It has previously been shown [3] that the displacement field on the fusion surface is mainly affected by the lateral solidification shrinkage that is perpendicular to the weld line. Based on conservation of mass, the lateral solidification contraction \(\chi_{\text{Sh}}\) for a confined semisolid domain can be expressed as:
where $\alpha = \frac{2\rho_l}{\rho_s}$ is the linear shrinkage coefficient, $\rho_l$ and $\rho_s$ are the liquid and solid densities respectively, and $Y_o$ and $g_s$ denote the lateral length and volumetric solid fraction. For a small solidification increment, equation (2) can be rewritten in differential form:

$$dY_{sh} = \frac{1}{3} Y_o (1 - \alpha) g_s \frac{2}{3} d g_s$$

Integration of equation (3) yields the gradual, accumulation of the lateral solidification contraction within the confined space as a function of solid fraction. Since the semisolid is not able to transfer stress before a continuous solid bridge forms across the confined domain, i.e. mechanical coalescence, the integration domain is limited to values of solid fraction at which the semisolid is percolated, i.e.:

$$Y_{sh\|t} = \int_{g_s|_{p}}^{g_s|_{t}} \frac{1}{3} Y_o (1 - \alpha) g_s \frac{2}{3} d g_s = Y_o (1 - \alpha) \left( \sqrt{\frac{2}{3} g_s|_{t}} - \sqrt{\frac{2}{3} g_s|_{p}} \right)$$

In Equation (4), $Y_{sh\|t}$ represents the evolution in linear solidification contraction with time, $g_s|_{t}$ denotes the average solid fraction of the confined space as a function of time, and $g_s|_{p}$ represents the average solid fraction at percolation, assumed to occur at a value of $g_s = 0.95$. The confined elements used in this study are shown in Figure 3. These elements, given the name bar elements, lie along the $Y$ direction connecting the weld center to the fusion surface. The ensemble of the bar elements and their corresponding displacement functions ($Y_{sh\|t}$), where the index $i$ represents an individual bar element, yields the Dirichlet boundary condition acting on the fusion surface of the thermomechanical module:

$$\bar{U}_{\partial\Omega_{\text{fusion}}|\text{base metal}} = \bar{D}(\mathcal{X}_{t}) = \begin{cases} 
D_Y|_{t} = Y_{sh\|t}^i \\
D_X|_{t} = D_Z|_{t} = 0 
\end{cases}, \quad \mathcal{X} \in A_Y^i$$

where the term $A_Y^i$ refers to the projection of bar element $i$ onto the portion of the fusion surface containing the given point in $D(\mathcal{X}_{t})$.

Figure 3. The bar element used to obtain the local solid fraction within the semisolid weld.

It should be noted that the bar elements are conceptual only; no simulation is performed directly on them. The displacement field given by Equation (5) is obtained by determining the average evolution in fraction solid with time within each bar element, i.e. $g_s|_{t}$, and then applying Equation (4) to
calculate the correct displacement value. The evolution in fraction solid is generated from the meso-scale solidification model of Zareie Rajani and Phillion [15] for AA6061 welds to reconstruct the 3D microstructure of the semisolid weld. The salient features of this model are presented below.

Through a 3D unstructured grid, the meso-scale solidification model first generates an ensemble of elements representing the microstructure of the weld composed of both columnar and equiaxed grains. As Figure 4a shows, the columnar grains are extended from the fusion boundary towards the center of the weld, while the equiaxed grains are located at the center of the weld. Only one half of the weld is modeled due to symmetry. Weld microstructure varies as a function of welding parameters. The model contains a lookup table linking welding parameters to equiaxed and columnar grain sizes, allowing different microstructures (unstructured grids) to be created based on the choice of welding conditions.

After discretization, solidification within the developed grains is simulated through tracking of the solidification fronts splitting the grains into separate solid and liquid regions [9, 12, 15]. Tracking of the solidification front in each grain is carried out by combining an evolving temperature field within the weld pool generated by the Rosenthal equation [15, 20, 21] with a fraction solid curve for AA 6061 generated by Thermocalc for Scheil solidification. As Figures 4b-c indicate, the meso-scale solidification model yields a microstructure weld composed of solid grains and a network of micro liquid channels at different times during the welding process; the empty space represents the liquid channels spreading along the grain boundaries. The solidification module predicts the evolving semisolid microstructure morphology during the welding process. The corresponding evolution in solid fraction can be averaged over any arbitrary confined space. The solidification module performs this averaging to obtain the transient solid fraction within each bar element to allow for calculation of the displacement field on the fusion surface. The simulated microstructure can also be used to assess the healing ability of the semisolid weld. The average width of the micro liquid channels is assumed as the relevant criterion, where wider channels improve the liquid feedability [2, 12].

![Figure 4.](image)

Figure 4. The unstructured grid representing the microstructure of a weld fabricated by welding speed of 3 mm/s and welding current of 120 A (a). The microstructure of the same weld during welding at t=0.2 s (b) and t=0.6 s (c).

2.3. Solution technique

Once the solidification module computes the displacement boundary condition acting on the fusion surface of the base metal, the thermomechanical analysis module simulates the evolution of the reaction forces on the base metal during welding. Equation (1) is then applied to extract the transient force field that deforms the semisolid weld. Since the lateral component of tensile force plays the key role in welding hot cracking [3], the tensile force components in Y that apply on bar elements with \(g_s > g_s|_{p}\) are averaged and then divided by the percolated area of the fusion surface to obtain the
average tensile stress acting on the semisolid weld. In order to gain insight into hot crack susceptibility, the average tensile stress values are then compared against known critical tensile stress values from the literature. A recent experimental study by Giraud and et al. [22] showed that the percolated semisolid AA 6061 cannot bear tensile stresses greater than 5 MPa. This value is considered as the critical criterion for defect formation and thus average tensile stresses greater than 5 MPa are assumed to cause excessive deformation and consequently initiate defects.

3. Results and discussion

The calculated average tensile stresses acting on the fusion surface of unclamped AA 6061 semisolid welds as a function of time fabricated by various welding parameters are shown in Figure 5 for different welding speeds between 2 and 5 mm/s. By comparing the results within individual figures it can be seen that increasing the welding current at constant welding speed generates larger average tensile stresses on the fusion surface, increasing the risk of severe deformation within the semisolid weld. Such an observation can be explained through the shrinkage displacement. By increasing the welding current, larger welds form, and as demonstrated in Equation (2), lead to larger amounts of solidification contraction. Higher magnitudes of shrinkage contraction will then create larger reaction forces on the fusion surface. This result matches prior experimental studies [3] where it is shown that high welding current and large weld pools increase the risk of hot cracking.

Figure 5. The calculated average tensile stress for various welding currents at welding speeds of: (a) 2 mm/s; (b) 3 mm/s; (c) 4 mm/s; (d) 5 mm/s.

In terms of welding speed, Figure 5 indicates that this parameter greatly affects the average tensile stress deforming the semisolid weld. At a low welding speed of 2 mm/s, Figure 5a, the maximum average tensile stress is relatively low. With increasing welding speed to 3 and 4 mm/s, Figures 5b and 5c, the maximum average tensile stress significantly rises, approaching the critical condition for defect formation. However, a further increase in welding speed to 5 mm/s, Figure 5d, appears to result in a decrease in the maximum average tensile stress. In other words, the simulations predict that the maximum average tensile stress and consequently the susceptibility to hot cracking are highest at an intermediate range of welding speeds. This result can be explained through the interaction between two main factors that control the material flow within the base metal: 1) solidification shrinkage causing material flow within the base metal since larger welds are accompanied by more lateral solidification contraction and consequently bigger driving forces for the materials flow, and 2) the
amount of resistance against material flow that strongly depends on the temperature of the base metal since colder base metals are accompanied by higher elastic moduli and larger yield strengths. Therefore, according to the Newton’s third law of motion, cold base metals and large welds generate high magnitudes of reaction forces, while hot base metals and smaller welds create lower magnitudes of reaction forces. As a result, the small average tensile stresses observed at low welding speeds can be linked to the excessive softness of the base metal that stems from high temperature conditions during slow welding. By increasing the welding speed, the heat input decreases, leading to a colder base metal. Consequently, the reaction force and the average tensile stress deforming the semisolid weld increase. Although the base metal is coldest at high welding velocities, the reaction forces do not keep growing since there is a significant drop in the size of the weld. In this simulation, by increasing the welding speed from 4 mm/s to 5 m/s at a constant welding current of 120 A, the depth of weld penetration decreased from 2 mm to 1 mm. It is hypothesized that very small welds do not generate enough linear solidification contraction to maintain the ascending trend of the reaction forces.

![Figure 6](image)

*Figure 6. The average tensile stresses on the weld fusion surface under different constraining conditions.*

| Welding speed (mms⁻¹) | Welding current (A) | Average thickness of micro liquid channels (µm) |
|-----------------------|--------------------|-----------------------------------------------|
| 2                     | 110                | 10±2                                          |
| 3                     | 105                | 11±2                                          |
| 3                     | 120                | 13±3                                          |
| 4                     | 110                | 10±3                                          |
| 4                     | 130                | 6±1                                           |
| 5                     | 105                | 9±2                                           |
| 5                     | 125                | 8±1                                           |
| 5                     | 140                | 8±2                                           |

Table 1. The average thickness of the micro liquid channels for various welding parameters.

Another welding parameter that is well known to affect the susceptibility of the weld to hot cracking is the constraining condition of the weld [3]. In Figure 6, three different constraining conditions are compared for a weld produced at a speed of 3 mm/s using a current of 120 A. In the first, the back surface of the plate was clamped \((\bar{U}_0 = 0)\). In the second and third, the back surface was displaced in tension along the \(Y\) direction. The displacement was initiated at the time corresponding to the time that at least one of the bar elements within the semisolid weld had percolated. The displacement reached the maximum value, 50 µm and 100 µm, when the weld had fully solidified. As can be seen in the figure, the application of tensile displacement on the back surface of the plate during welding results in the average tensile stresses along the fusion surface exceeding the critical value, making the weld severely susceptible to defect formation.

Initiated defects within the semisolid weld will lead to hot cracking if the network of micro liquid channels fails to heal the defects, i.e. feed the molten aluminum adequately. Hence, in addition to the stress applied to the semisolid weld, the feeding ability of the microstructure has to also be known in order to assess hot cracking susceptibility. Table 1 lists the average thickness of the micro liquid channels within a percolated microstructure for various welding parameters. The results are extracted from the solidification module. Based on the obtained results, the liquid films present at a welding
speed of 4 mm/s and current of 120 A are the narrowest, and thus, have the lowest healing ability. Further discussion of the micro liquid channel widths can be found in [15].

4. Conclusion
The present model proposes a method to couple simulations of solidification in a weld pool at the meso-scale with thermomechanical deformation of the base metal in order to assess hot cracking susceptibility. The solidification module reconstructs the 3D microstructure of semisolid AA 6061 welds, enabling determination of the average thickness of the micro liquid channels within the semisolid weld, and also the linear solidification contraction. The thermomechanical module utilizes the displacements imparted by the weld shrinkage along with various boundary conditions to extract the tractions on the fusion surface that deforms the semisolid weld during solidification.

Based on the obtained results, the semisolid weld undergoes the maximum deformations and also the lowest healing ability at a moderate welding speed of 4 mm/s and a high level of welding current. The results also indicate that any external tensile stress during welding will further increase the semisolid weld’s susceptibility to hot cracking. Future work will focus on development of a simulation to localize the deformations within the semisolid weld based on the tractions on the fusion surface.

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