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Free Surface Modeling of Contacting Solid Metal Flows Employing the ALE formulation

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Abstract. In this paper, a numerical problem with contacting solid metal flows is presented and solved with an arbitrary Lagrangian-Eulerian (ALE) finite element method. The problem consists of two domains which mechanically interact with each other. For this simulation a new free surface boundary condition is implemented for remeshing of the boundary elements. It uses explicitly that the integral of the convective velocity along a boundary element remains zero. Steady state solutions are obtained only if the integral of the convective velocities along each free surface boundary element remains zero. The new remeshing option for the free surface is tested on a cladding problem employing friction stir welding (FSW). The problem describes two elasto-viscoplastic aluminum material flows which mechanically interact.

Introduction

Many (thermo) mechanical processes exist where two contacting solid materials move with respect to each other to form a joint at the interface, such as seam welding, friction surfacing, friction welding and (roll) cladding. In most cases the quality of the bonding at the interface depends on the local conditions during processing (pressure, rate of plastic deformation, temperature), the thermo mechanical properties of the materials and the presence of oxide layers on the materials. Optimization of the process conditions requires in-depth understanding of the locally occurring phenomena. Numerical models that describe the processes that take place while processing, form a useful tool to improve and optimize the processes.

Various approaches exist to model these types of (thermo) mechanical processes. The simplest case is where the process is simulated as a single domain process [1]. There is no interface between the different materials and stick conditions are assumed without considering how the bonding process occurs on a global or local scale in time. Also models exist which assume a symmetry boundary condition at the interface where the two material flows coincide [2].

However, for simulations which do not have a symmetry line or where sticking behavior does not apply unconditionally, different approaches are necessary. Then, a multiple material domain model is required where the two deformable bodies interact with each other in some way. Such models can be rarely found for problems with large deformable material flows. Some single domain models exist where the interface at the seam weld can deform mechanically [3,4], but these apply to a case with one type of material only. In this work the use of the finite element method is pursued, and then especially, the arbitrary Lagrangian-Eulerian (ALE) formulation, to adequately describe the behavior of multiple materials domains up to large deformations. The description of free, non-contacting surfaces, during the thermo mechanical processing of the material flows, needs special attention in this case.

Free surface model development

The ALE method is a finite element method formulation which is suitable for describing large deformation processes. Compared to purely Eulerian formulations, it has the beneficial ability of describing moving boundaries and large volume changes of the computational domain. Compared to the Lagrangian formulation, the mesh displacements are not coupled directly to the material displacements and therefore large deformations can be modeled without distortions of the mesh.

However, the modeling of moving free surfaces with the ALE method needs a special treatment as compared to the Eulerian and Lagrangian formulations where the treatment of a free surface is straightforward. In case of the Eulerian formulation the boundary does not move and in case of the Lagrangian formulation the free surface moves with the same displacement as the local material flows themselves as the mesh is directly coupled to the material. Employing the ALE formulation the decoupling of the material flow from the finite element mesh, requires remapping of the mesh which is not straightforward in cases of moving free surfaces.

The condition for remeshing of the boundary elements at the free surface is explained here below. It starts by defining the convective velocity vector $\boldsymbol{c}$, which represents the difference between the material and the mesh velocities vectors, $\boldsymbol{v}_m$ and $\boldsymbol{v}_g$, respectively [5]:

$$\boldsymbol{c} = \boldsymbol{v}_m - \boldsymbol{v}_g. \tag{1}$$

At the free surface boundary, "no particles" can cross the free surface. This condition is expressed by setting the normal mesh velocity at the free surface equal to the normal material velocity [6,7], as often used in fluid mechanics:

$$(\boldsymbol{v}_m - \boldsymbol{v}_g)\cdot\boldsymbol{n} = 0 \qquad \text{or} \qquad \boldsymbol{c}\cdot\boldsymbol{n} = 0, \tag{2}$$

where $\boldsymbol{n}$ is the normal vector on the free surface.

This last equation is applicable for continuous bodies, but it does not apply straightforwardly to discretized domains as with finite element methods. Then, the integral formulation of Eq. 2 needs to be applied on each free surface boundary element (e) of a body:

$$\int_{\Gamma_e} \boldsymbol{c}\cdot\boldsymbol{n}\, \mathrm{d}\Gamma = 0, \tag{3}$$

where Γ represents the total free surface of a discretized body and the subscript e the free surface of an element of that body. Last condition is applied on the surface of every individual element on the free surface boundary.

Implementation. The ALE method used in this work is incorporated in the in-house developed DiekA simulation software. It employs the so-called semi-coupled formulation with a predictor and a corrector step. In this formulation an updated Lagrangian displacement step, $\Delta\boldsymbol{u}_\mathrm{m}$, is followed by a second, correction step, projecting the mesh back, $\Delta\boldsymbol{u}_\mathrm{r}$. The displacement steps are related to the material and mesh velocities in the following way:

$$\boldsymbol{c} = -\frac{\Delta\boldsymbol{u}_\mathrm{r}}{\Delta t}; \quad \boldsymbol{v}_m = \frac{\Delta\boldsymbol{u}_\mathrm{m}}{\Delta t}; \quad \boldsymbol{v}_g = \frac{\Delta\boldsymbol{u}_\mathrm{g}}{\Delta t}, \tag{4}$$

where Δt represents the time step and $\Delta\boldsymbol{u}_\mathrm{g}$ the mesh displacement. Substituting Eq. 4 into Eq. 3 yields the following criterion that needs to be solved for each surface boundary element:

$$-\int_{\Gamma_e} \Delta\boldsymbol{u}_\mathrm{r}\cdot\boldsymbol{n}\, \mathrm{d}\Gamma = 0. \tag{5}$$

The use of Eq. 5 for 2D problems is now demonstrated. Assume a free surface element *i* with nodes *j* and *j+1*, as indicated in Fig 1. Firstly, a solution is found for the updated Lagrangian step with $\Delta \boldsymbol{u}_{\mathrm{m}}$ displacements (0). Subsequently, a prescribed $\Delta \boldsymbol{u}_{\mathrm{r}}$ is used for remapping node *j*. Then $\Delta \boldsymbol{u}_{\mathrm{r}}$ for node *j+1* needs to be determined (1). Next, it is prescribed that node *j+1* can move along a vector ***d*** (2a) or on a circle with radius *r* (2b) for remeshing. Option 2a is preferred for moving the node in a specific direction and the element length can change. Option 2b is preferred for keeping the element length fixed to a radius *r*. By using one of the two options, the new position of node *j+1* is determined by solving Eq. 5 (3). For this algorithm, $\Delta \boldsymbol{u}_{\mathrm{r}}$ of the first node on a line of boundary elements should be prescribed and the $\Delta \boldsymbol{u}_{\mathrm{r}}$ of subsequent nodes is determined according to Eq. 5.

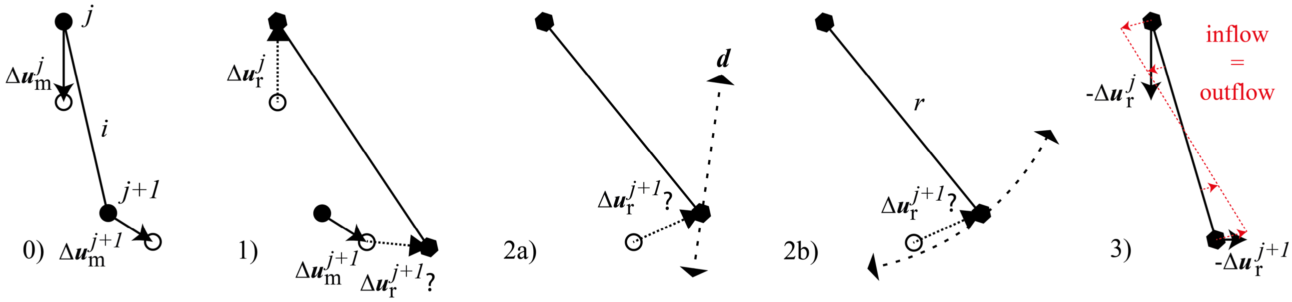

Figure 1. Remeshing options for the free surface boundary condition: 2a) moving of the nodes in one direction ***d*** or 2b) keeping an element length *r* fixed.

Cladding employing friction stir welding

FSW [8] is a relatively new solid-state joining technology. Due to its solid state character, alloys formerly considered unweldable due to solidification problems after welding can be welded well, such as advanced precipitation based Al2xxx and Al7xxx aluminium alloys. Here, we consider the development of an innovative FSW tool containing internal channels to (i) locally modify the material micro structure and/or composition and (ii) locally deposit thin layers of various types of materials, such as pure Al clad layers for improving corrosion protection. A possible design to realize the local deposition of a clad layer is shown in Fig. 2. The tool shoulder is equipped with internal channels that allow delivery of filler type of material. Depending on the channel architecture used, filler material can be deposited on top of the work piece surface and/or also mixed with the work piece surface region. The cladding is done in the solid state avoiding many problems with solidification and interface reactivity often observed with other surface modification techniques, such as laser surface engineering, plasma spraying or casting. The top view of the process with a rotating and translating tool is shown in Fig 3. The pattern of deposited material as a function of the movement of the tool relative to the work piece is indicated.

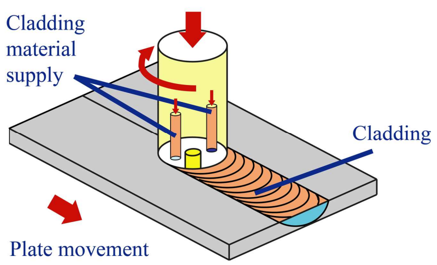

Figure 2. Schematic representation of friction stir welding with cladding.

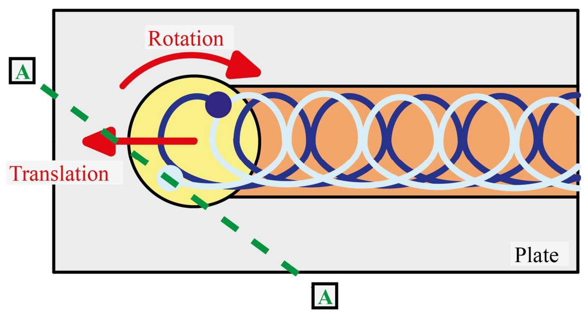

Figure 3. Top view of the cladding process with cross section A-A indicated.

Proper numerical simulations accelerate the development of the tool as more knowledge is obtained about the spreading of the cladding material over the work piece surface. The cladding material should be distributed uniformly over the surface by designing a suitable geometry of the tool. Other interesting phenomena include the microstructural changes that take place in the work piece and clad material over time as a consequence of the generated stresses and heat. The simulation of the process shown in Fig. 2 requires comprehensive three dimensional numerical methods. As a start a 2D representation of the cladding process is considered as shown schematically in Fig. 4. It represents the cross section A-A depicted in Fig. 3.

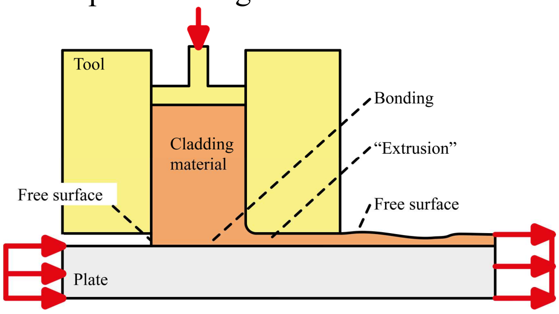

Figure 4. 2D representation of the cladding process at cross section A-A.

In the 2D model the plate has a constant velocity which equals the rotating velocity of the tool relative to the work piece. The contribution of the translational speed of the plate is neglected. Since the process is dependent on the relative speed of the tool with respect to the work piece, in the simulations the tool is held stationary and the plate moves beneath it, while the cladding material is deposited on top of the plate.

Geometry and boundary conditions. The geometry and boundary conditions of the isothermal 2D plane strain problem solved in this work are shown in Fig. 5, which is a simplified version of Fig. 4 as no separate piston is present at the top of the cladding material to exert a compressive deposition force. Instead a distributed force is applied at the inlet of the cladding material. Furthermore, the plate has a constant horizontal velocity prescribed.

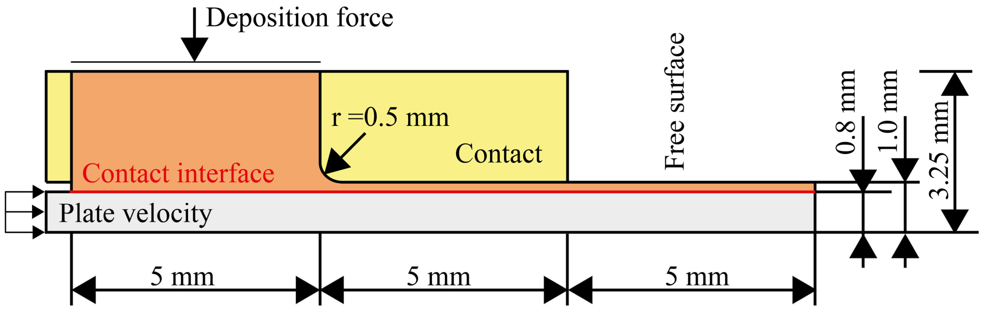

Figure 5. Geometry of the cladding problem.

Material properties. The cladding material flow has similarities to extrusion. In this case, material is pressed through a channel onto the plate at sufficiently elevated temperatures. Therefore, the material behavior is taken identically as in Lof [9] who studied extrusion flows of Al6063. Von-Mises elasto-viscoplastic material behavior material is included using the Sellars-Tegart hardening law. It relates the equivalent viscoplastic strain rate $\dot{\kappa}$ to a flow stress σ_y:

$$\sigma_y(\dot{\kappa})=s_m \operatorname{arcsinh}\left(\left(\frac{\dot{\kappa}+\dot{\kappa}_0}{A} e^{Q/RT}\right)^{\frac{1}{m}}\right), \tag{6}$$

where s_m , m and A are material dependent strain sensitivity parameters, Q is the apparent activation energy of the process during viscoplastic flow, R is the universal gas constant, T is the absolute temperature and $\dot{\kappa}_0$ is the initial equivalent viscoplastic strain rate. The values of the material parameters as employed in this work are summarized in Table 1.

Table 1. Material parameters for AA6063[9]

	Symbol	Value
Elastic properties	E [GPa]	40
(T=673 K)	ν [-]	0.33
Plastic properties	s_m [MPa]	25
	m [-]	5.385
	A [1/s]	$5.91{\cdot}10^9$
	Q [J/mol]	$1.4{\cdot}10^5$
	R [J/molK]	8.314
	$\dot{\kappa}_0$ [-]	$5.0{\cdot}10^{-3}$

Free surface. The newly developed remeshing procedure of the free surface as described above has been used. The same algorithm has been applied for the remeshing after the Lagrangian step at the contact interface between the tool and cladding material.

Bonding. At this stage a relatively simple function to describe the generation of bonding at the interface of the moving material flows has been considered. Two cases are selected at the interface between the cladding material and the work piece. In the first case no bonding takes place. A Coulomb type of friction in the tangential direction is employed and a penalty function in the normal direction. In the second case an adhesion type of bonding is employed as described in Akkerman [10]. This adhesion model keeps the two layers connected as a bond. In both cases a friction coefficient of 0.5 is used.

Simulation of cladding

The cladding simulations are performed by prescribing a force of 260 N which is equivalent to 52.0 MPa and a velocity of 0.4 m/s. One simulation is performed without adhesion between the layers and the other simulation with adhesion.

Non-adhesive model for cladding. The velocity magnitude distribution of the non-adhesive model is shown in Fig. 6. Cleary, there is slip between the two layers along its whole length which results in a lower velocity of the cladding material as compared to the work piece plate. Moreover, there is no steady state solution and cladding material is vertically oscillating downstream.

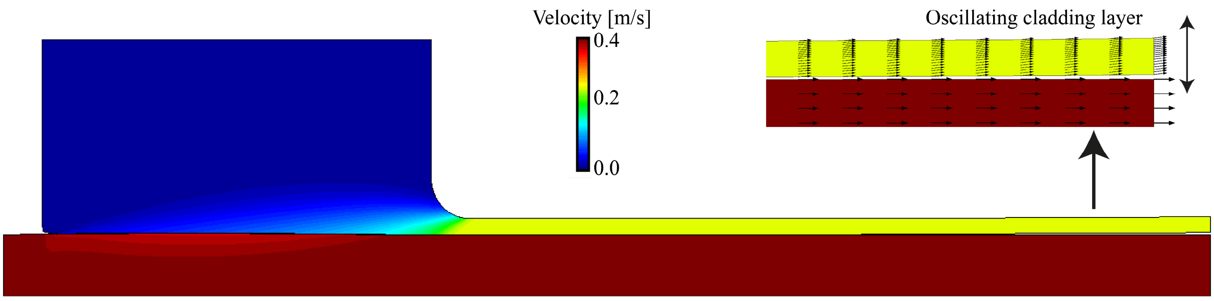

Figure 6. Velocity magnitude distribution of the model without adhesion at 0.4 m/s plate velocity.

Adhesive model for cladding. The velocity magnitude distribution of the adhesive model is shown in Fig. 7. Now, there is stick behavior between the two layers which results in equal velocities downstream of the work piece plate and the clad layer; the oscillating behavior disappeared. The stick behavior is gradually built up from slip at location 1 to stick at location 2, see Fig. 7.
For future work, the influence of the velocity of the plate, the geometry of the tool, different types of materials and the force on the cladding material will be researched. However, first a correct bonding function is required which describes the bonding phenomenon of the two contacting bodies and the heat generation by friction should be added.

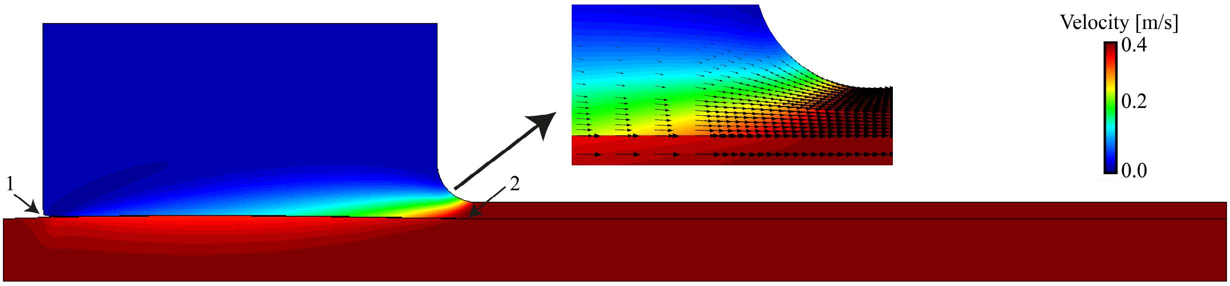

Figure 7. Velocity magnitude distribution of the model with adhesion at 0.4 m/s plate velocity.

Conclusions

In this work, cladding of aluminum 6063 on aluminum 6063 is simulated at elevated temperatures. A newly developed remeshing algorithm for free surfaces is included in an ALE finite element method and a simple adhesion bonding model is used. Future work will involve adding an experimentally validated bonding function and temperature dependency can be added. Temperature dependency is important for determining the heat generation by partly friction between the plate and the tool and partly by friction between the cladding material and the plate.

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