Journal of Computational Physics 270 (2014) 478–489

Contents lists available at ScienceDirect

Journal of Computational Physics

www.elsevier.com/locate/jcp

Implicit Geometry Meshing for the simulation of Rotary Friction Welding

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ARTICLE INFO

Article history:
Received 11 September 2013
Received in revised form 26 March 2014
Accepted 5 April 2014
Available online 13 April 2014

Keywords:
Rotary Friction Welding simulation
Implicit Geometry Meshing
Carreau fluid law
Computational fluid dynamics

ABSTRACT

The simulation of Rotary Friction Welding (RFW) is a challenging task, since it states a coupled problem of phenomena like large plastic deformations, heat flux, contact and friction. In particular the mesh generation and its restoration when using a Lagrangian description of motion is of significant severity. In this regard Implicit Geometry Meshing (IGM) algorithms are promising alternatives to the more conventional explicit methods. Because of the implicit description of the geometry during remeshing, the IGM procedure turns out to be highly robust and generates spatial discretizations of high quality regardless of the complexity of the flash shape and its inclusions.

A model for efficient RFW simulation is presented, which is based on a Carreau fluid law, an Augmented Lagrange approach in mapping the incompressible deformations, a penalty contact approach, a fully regularized Coulomb-/fluid friction law and a hybrid time integration strategy. The implementation of the IGM algorithm using 6-node triangular finite elements is described in detail. The techniques are demonstrated on a fairly complex friction welding problem, demonstrating the performance and the potentials of the proposed method. The techniques are general and straight-forward to implement, and offer the potential of successful adoption to a wide range of other engineering problems.

1. Introduction

Rotary Friction Welding (RFW) is a solid state welding process widely used in the automotive, aeronautic and railway industries. In this joining process, typically one part is clamped while the other one is spinning and pressed onto the weld surface. Once enough frictional heat is generated, the spindle breaks and the two parts are forged together [14,15]. The main bonding mechanisms are diffusion and in case of two dissimilar materials the formation of intermetallic phases. Since no additives are needed during the procedure, the weld is quite uncontaminated in comparison to conventional arc welding processes. Other major benefits are the symmetry of the joint, the stability of the process, the short cycle times and the smaller heat affected zone [31]. Besides RFW, other processes such as Friction Stir Welding (FSW) [7], Linear Friction Welding (LFW), Inertia Friction Welding (IFW) and Orbital Friction Welding (OFW) exist, differing mainly in the relative kinematic movement of the weld partners.

The motivation for modeling these joining processes includes more understanding of the physics [12,17], prediction of process parameters [32,33], tool optimization [20–22] and microstructure and defect modeling [16,27]. Most of the proposed

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http://dx.doi.org/10.1016/j.jcp.2014.04.014
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models can be divided into solid mechanic (CSM) and fluid dynamic (CFD) approaches. Representative work based on the CSM approach can be found in [16,19,36]. As elastic effects are accounted for in these methods, phenomena such as residual stresses or thermal expansion can be properly mapped by the simulation. However, the price for this is usually a higher computational expense. The CFD models treat the solid phase of the material as a fluid with very high non-Newtonian viscosity. This is a very popular approach in modeling of FSW, see for example [9,10,18,25,27,35], but it is also applied to RFW and IFW [12,26,32,33]. Various suggestions have been made for the shear viscosity–strain rate dependency, including the implementation of Norton's law [9,12,18,25,26], Sheppard–Wright's law [9,10,27,35] or Carreau's fluid law [32,33]. A very detailed and profound comparison of CSM and CFD based approaches is found in [6] at modeling FSW.

The major difficulty in modeling of RFW, both for the CSM and the CFD methods, is the treatment of the large plastic deformations. In literature Eulerian [1,4], Arbitrary Lagrangian Eulerian (ALE) [18,24,34], Lagrangian [2,12,17,26,32,33,36] or combined formulations [9,6,13] of the governing equations are proposed. This formulation type is inherently related to the interpolation mechanism of the corresponding degrees of freedom. Either meshless methods, like the Smoothed Particle Hydrodynamics method (SPH) [16,21,27] or the Natural Element Method (NEM) [2], or finite element based approaches are discussed in the literature [9,6,12,13,17,26,33,35,36]. In particular at FSW modeling meshless methods are favourable since they natively map mixing of the material, while costly remeshing algorithms are expendable. However, a certain difficulty of meshless methods is that the boundary of the domain is somewhat imprecise, which makes contact calculations more challenging. This argument certainly contributes to the fact that concerning IFW and RFW models, which basically are contact problems of two deformable parts, most works base on conventional Lagrangian based Finite-Element methods [12,17,26,33,36] making efficient and robust meshing techniques indispensable.

The current contribution seizes the suggestion of applying Implicit Geometry Meshing (IGM) techniques for mesh generation and remeshing at the simulation of RFW [29,30]. The major benefit of IGM in front of conventional Advancing Front Meshing (AFM) algorithms is its extreme robustness and high performance for mapping the vast plastic deformations, while at the same time the mesh generation algorithm and topology treatment is straightforward and can be implemented using a few dozen lines of source code only.

The structure of the paper is as follows: First a brief introduction of the model is given, including the material law, the finite element formulation and the contact law. Next, the applied IGM procedure and its application to the RFW simulation is described in detail. A representative friction weld problem, which is rather complex with respect to the geometry and the deformations, demonstrates the excellent performance of the method. Finally, the benefits and potentials of the technique are discussed and conclusions are given.

1.1. *A remark on notation*

Scalars are denoted by non-boldfaced letters such as $\bar{r}$, $\sigma_{0,R}$ and n. Tensorial expressions of higher order than zero are stated as boldfaced symbols, for example $\boldsymbol{s}$, $\boldsymbol{\sigma}$ and $\boldsymbol{D}$. Their components with respect to a vectorial basis as well as nodal values and scalars being arranged in matrices are denoted by blackboard bold symbols, as in $\mathbb{M}$, $\mathbb{v}$, $\mathbb{O}$ and $\mathbb{A}_{cap}$. Domains are marked by calligraphic letters, for instance like $\mathcal{B}_t$ or $\mathcal{B}_0$.

2. Modeling of Rotary Friction Welding

2.1. *Governing equations*

The material behavior of the work pieces is constituted by a fluid law of Carreau type [32,33]. Thus, the non-Newtonian viscosity amounts to

$$\mu(\dot{\varepsilon}_{vM},\Theta)=\left[1+\left(\left(\frac{\sigma_0(\Theta)}{3\dot{\varepsilon}_0\mu_0}\right)^{\frac{n}{1-n}}\frac{\dot{\varepsilon}_{vM}}{\dot{\varepsilon}_0}\right)^2\right]^{\frac{1-n}{2n}}(\mu_0-\mu_\infty)+\mu_\infty, \tag{1}$$

involving the von-Mises equivalent strain rate $\dot{\varepsilon}_{vM}$, the plastic reference strain rate $\dot{\varepsilon}_0$, the Norton–Bailey exponent n, the temperature dependent flow stress $\sigma_0(\Theta)$ and the two saturation viscosities μ_0 and μ_∞ [8]. The flow stress curve is assessed by a Johnson–Cook power approach of the form

$$\sigma_0(\Theta)=\begin{cases}\sigma_{0,R}[1-(\frac{\Theta-\Theta_R}{\Theta_M-\Theta_R})^m], & \Theta<\Theta_M,\\ 0, & \Theta\geq\Theta_M,\end{cases} \tag{2}$$

where $\sigma_{0,R}$ is the yield limit at room temperature Θ_R, Θ_M is the melt temperature and m the Johnson–Cook exponent [23]. In terms of these, the deviatoric stresses are given by

$$\boldsymbol{s}=2\mu(\dot{\varepsilon}_{vM},\Theta)\,\mathrm{dev}(\boldsymbol{D}). \tag{3}$$

The incompressibility criterion is met by an Augmented Lagrange method [33]. The motion of a material point $\boldsymbol{x}$ is governed by the balance of linear momentum