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Application of Adaptive Element-Free Galerkin Method to Simulate Friction Stir Welding of Aluminum

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Abstract

The modeling of friction stir welding (FSW) is challenging as severe plastic deformation is present. This is in particular the case as typical finite element methods are employed. In this study we use a meshfree technique to model the material flow during the FSW process. We employ the Element-Free Galerkin method (EFG) as approximation method. A mortar contact is used to account for the stirring effect and heat generation from the frictional contact. A two-way adaptive method (rh-adaptive) during the coupled thermomechanical process is used to overcome potential numerical problems arising from the extensive mesh distortion and material deformation. This means, the mesh is globally refined with perusing an anisotropic tetrahedral mesh (h-adaptive). At the same time, a completely new mesh is built based on the old mesh (r-adaptive). Finally, we perform the simulation method on an aluminum sheet with a cylindrical tool to exemplarily show the applicability of the adaptive Element-Free Galerkin method. In future work, the obtainable deformation and temperature history from the thermomechanical simulation will be used to predict the final micro-structure after the welding process.

Keywords: Friction Stir Welding, Meshfree Methods, Adaptivity

Nomenclature

FSW Friction Stir Welding

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EFG	Element-Free Galerkin Method
ALE	Arbitrary Lagrangian Eulerian
$\boldsymbol{X}$	position vector
Φ_I	shape function for node I
u_I	nodal displacement at location X_I
$\boldsymbol{p}$	linear basis functions vector
T	temperature
h	dilation parameter
W	weight function
ω	set of particles

1. Introduction

In order to design light weight structures for ever emerging demands, developing suitable joining processes are essential. Among many others, a solid state joining technique is Friction Stir Welding (FSW). FSW was first invented at the Welding Institute (TWI), UK, in 1991 [1]. FSW has been proven to be effective in order to weld hard-to-weld materials as well as joining plates of different materials or thickness. During FSW, a rotating non-consumable tool with a shoulder is inserted into the edges of the workpieces which are joint, see Fig. 1 [2]. As the rotating is advancing into the workpieces, two phenomena are mainly responsible for generating heat. These are the frictional contact between the tool/shoulder and the workpiece as well as the plastic deformation of the workpiece. For a comprehensive overview on the FSW process, refer to the review article by Mishra and Ma [3].

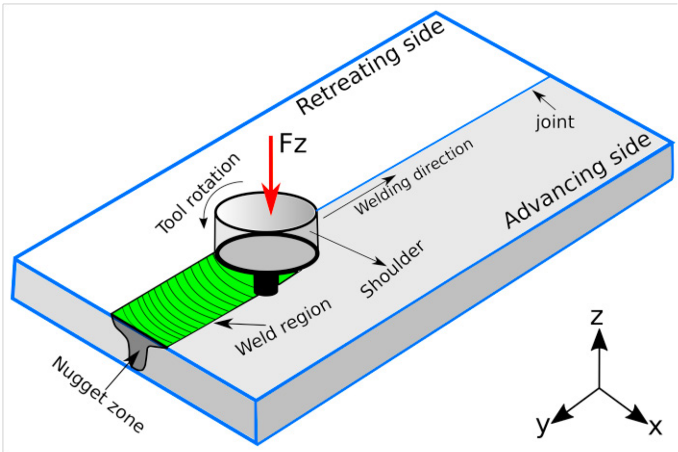

Fig. 1. Schematic illustration of the FSW process.

FSW is a rather complex process comprising several highly coupled and non-linear physical phenomena. These phenomena include large plastic deformation, material flow, mechanical stirring, surface interaction between the tool and the workpiece, dynamic structural evolution and heat generation resulting from friction and plastic deformation. To achieve a stable process, leading to a successful weld and good final mechanical properties of the FSW joints, depends on multiple parameters. These parameters include the type of joining material(s), the geometry of the tool, the rotation speed of the tool, the welding speed and the downward force applied to tool among others. Moreover, due to the non-linear coupled thermo-mechanical behavior of the system, it is difficult to predict for different parameter combinations the final mechanical properties of the joints. Since experimental tests are costly and time consuming, many researchers opted to use numerical simulations to model the FSW process.

From a number of possible numerical techniques to model the FSW process, the first candidate is the Finite Element Method (FEM) in its Lagrangian description of motion. However, FEM soon faces difficulties in order to model the severe deformation and plasticity around the tool. To circumvent the mesh distortion, the Eulerian description of motion in the sense of Computational Fluid Dynamics (CFD) can be employed, see for example [4]. In this approach the material is treated as a viscous incompressible non-Newtonian fluid. However, CFD approaches have problems in modeling free surfaces and the heat generation source in the FSW process [5]. Another approach to heal the mesh distortion problem is employing r-adaptive remeshing in the framework of the Arbitrary Lagrangian Eulerian (ALE) formulation. ALE does not add additional degrees of freedom and therefore it is effective to use it for modeling of steady state FSW process. Nevertheless, as the tool has to travel a long distance in simulating the full FSW process, the ALE approach may fail as well [6] since a fine mesh region is always needed around the tool. This problem is also reported in [7] as ALE could not circumvent severe distortion of the elements. Interested readers are referred to the recent comprehensive review on numerical modeling of FSW by He et al. [8].

Among all these approaches, a combined rh-adaptive method in the Lagrangian formulation seems to be most suited to approach the problem of FSW [9]. However, using FEM still encounters problems for three dimensional (3D) remeshing. Alternatives for FEM in this sense are the meshless methods such as the Element-Free Galerkin Method (EFG) [10] among many others. Meshfree methods are particularly useful when dealing with large plastic deformation and material failure [11]. As a result, in this study we employ an adaptive meshfree method to model the FSW process. Using an EFG method for modeling the FSW process was first done by Wu et al. [6]. We therefore apply a similar procedure proposed therein to simulate the FSW process with the aim of modeling the experiment as it is done in [12], including the prediction of the final microstructure of the joint after the FSW process correctly.

2. Simulation set-up

In the following, the details about the simulation set-up and the different techniques, used to model the FSW process are given.

2.1. Element-Free Galerkin Method (EFG)

The approximation method in this study is the EFG method which is based on the moving least square method developed by Belytschko et al. [10]. Similar to FEM approximation, in terms of the Lagrangian (material) coordinates, meshless approximation can be written as

$$\boldsymbol{u}^h(\boldsymbol{X},t) = \sum_{I\in\omega} \Phi_I(\boldsymbol{X})\, u_I(t), \tag{1}$$

where $\Phi_I(\boldsymbol{X})$ is the shape function for node I and u_I is the nodal parameter at the location $\boldsymbol{X}_I$, and ω is the set of particles where $\Phi_I(\boldsymbol{X}) \neq 0$. Please note, unlike FEM, $u(\boldsymbol{X}_I) \neq u_I$. As a result, treating displacement boundary conditions is different to that of FEM, see for example [13]. The shape function in EFG $\Phi_I(\boldsymbol{X})$ is defined as

$$\Phi_I(\boldsymbol{X}) = \boldsymbol{p}(\boldsymbol{X})^T\, \boldsymbol{A}(\boldsymbol{X})^{-1}\, W(\boldsymbol{X}-\boldsymbol{X}_I, h), \tag{2}$$

with

$$\boldsymbol{A}(\boldsymbol{X}) = \sum_{I\in\omega} \boldsymbol{p}(\boldsymbol{X}_I)\, \boldsymbol{p}(\boldsymbol{X}_I)^T\, W(\boldsymbol{X}-\boldsymbol{X}_I, h), \tag{3}$$

where h is the dilation parameter, $\boldsymbol{p} = [1\ x\ y\ z]^T$ the linear basis function vector, and W is the weight function, see [10] for more details. EFG is also a partitions of unity method [14]. However, since the EFG shape functions are not unity on the boundary, imposing the essential boundary conditions are different to FEM as mentioned before.

2.2. Adaptivity method

The severe deformation around the translating and rotating tool deforms the Lagrangian mesh excessively. This causes negative Jacobian for finite element meshes. EFG discretization will have fewer problems with severe deformation; however, for processes as FSW a strategy is still needed to overcome the mesh distortion problem. In this study we use a two way adaptive method. Therefore we use a concept of global remeshing based on unstructured tetrahedral mesh that can evolve around the stirring zone. To construct the EFG shape functions, a set of nodes are extracted from the tetrahedral mesh. The adaptive refinement will both refine the mesh up to a certain limited mesh size (h-adaptive) defined by the user as well as global remeshing with the same density of nodes (r-adaptive). The latter will heal the highly distorted mesh around the stirring tool. To recognize the areas to be refined, a point wise error indicator based on a shear deformation measure is used.

2.3. Solution and time stepping

The coupled thermo-mechanical problem in this study is solved in a staggered scheme. In such a scheme, the problem is divided into two steps: the mechanical steps and the iso-thermal step at each time increment. During the mechanical solution step, a constant temperature $T(\boldsymbol{X})$ is assumed. In the iso-thermal step, constant heat generation is assumed based on the mechanical step, i.e. plastic dissipation and friction. The assumption to uncouple the thermal and the mechanical problem is rational since the heat conduction occurs much slower than plasticity.

To solve the mechanical step, implicit solution technique is used using the Newton method for the nonlinear solution. This is a strong difference to other studies where often explicit time integration schemes are employed. The stable time step required for explicit time integration would be very small, requiring a long computation time for the FSW process which is of the order of seconds. To avoid small time steps in explicit time integration, other studies use mass scaling; see for example [7]. However, to avoid such, rather unphysical, assumptions, implicit time integration is employed that will eventually enables us to solve even longer time periods of the process.

2.4. Material model

The FSW tool is modeled as rigid with thermal conduction. For the specimen consisting of aluminum alloy, a temperature dependent linear elastic – ideal plastic material model is used for simplicity. In many other studies, for example [15], the Johnson-Cook material model is used for aluminum alloys such as AA2024. In Johnson-Cook material model, the stress is computed as a function of strain, strain rate and temperature. However, this model is intended for high velocity impact with much higher strain rates than FSW. Additionally, studies have shown that strain rate dependency for this alloy at the relevant strain rate range during FSW is negligible [16].

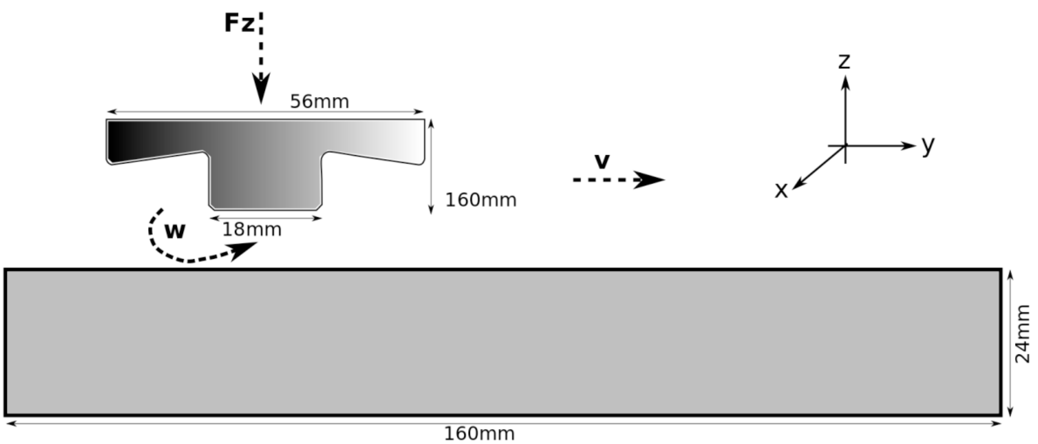

Fig. 2: Geometry of the tool and the workpiece.

2.5. Geometry and boundary conditions

The tool used in this study is of cylindrical shape with no features on its surface. The geometry of the tool and the workpiece in this study are shown in the Fig. 2. The workpiece is prevented to move in z-direction by fixing the bottom surface in this direction. Additionally, all side boundaries are fixed in x- and y-direction. During the plunging stage, the rotating tool moves only in z-direction. After this stage and in the welding stage the tool moves in the y-direction with a constant speed of $v = 25\ mm/s$, keeping its position in x- and z-direction fixed. The rotation speed of the tool is $w = 1200\ rpm$. The initial temperature of the whole systems is set to $T = 20°C$. A surface to surface forming mortar contact is chosen to handle the contact and friction between the tool and the workpiece. This contact formulation is also able to handle heat transfer.

All simulations are performed with the advanced general-purpose multiphysics simulation software package LSDYNA.

3. Results

Figure 3 shows the results of the simulation at different time steps. Although the initial mesh seems rather coarse (Fig. 3a), the applied framework adjusts the mesh density accordingly to the present deformation (Fig. 3b). The contour plots belong to different results such as temperature (Fig. 3b) and effective stress (Fig. 3 c)-d)). The implicit time steps to compute the mechanical solution was in the order of $\Delta t = 10^{-4} s$. The results in Fig. 3 clearly illustrate the flow of the material and the free surface, where the red areas indicate the stirring zone during the welding process. These first results show that the computational model based on the adaptive Element-Free Galerkin method is well suitable to effectively handle such complex process as friction stir welding.

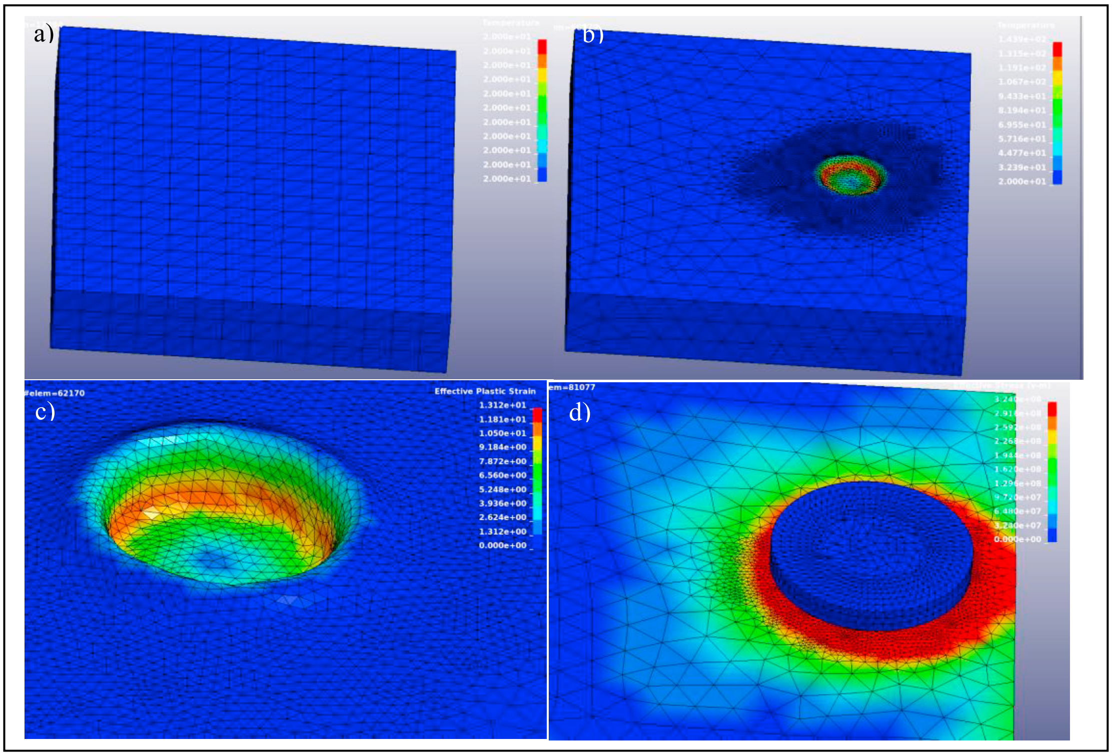

Fig. 3: Results of the adaptive modeling of FSW in different time steps: (a) The initial mesh (b) Temperature at 0.3803 s (c) Effective plastic strain at 0.6409 s (d) Effective stress at 0.9409s.

4. Conclusion

In this paper, we used a two-way adaptive meshfree method to simulate the friction stir welding process. Lagrangian description of motion is used. The Element-Free Galerkin method was employed as numerical approximation technique. We used implicit time integration scheme as well as a mortar surface to surface contact to handle the interaction between the tool and the work piece. The results showed that the current model is able to efficiently handle the complex thermo-mechanical phenomena during the FSW process. In the next step, the obtained deformation and temperature fields from this thermomechanical simulation will be compared to experimental results of FSW. Afterwards, these information will be used as input for a simulation to predict the resulting micro-structure after the welding process.

Acknowledgements

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