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Editorial

Challenges to Be Tackled in the Computational Modeling and Numerical Simulation of FSW Processes

Carlos Agelet De Saracibar

Department of Civil and Environmental Engineering, School of Civil Engineering, Technical University of Catalonia, UPC BarcelonaTech, 08034 Barcelona, Spain; carlos.ageletdesaracibar@gmail.com

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The computational modeling and numerical simulation of Friction Stir Welding (FSW) processes is an extremely challenging task due to the highly nonlinear and coupled nature of the physical problem and the complex computational issues that need to be properly tackled in the numerical model [1–6].

1. Physical Model

The FSW process is a complex problem due to the highly nonlinear and coupled nature of the physical problem. Different physical phenomena occur during the welding process, involving the thermal and mechanical interactions. The temperature field is a function of many welding parameters such as welding speed, welding sequence and environmental conditions. Formation of distortions and residual stresses in workpieces depend on many interrelated factors such as thermal field, material properties, structural boundary conditions and welding conditions. The challenging issues in physical modeling of the FSW process are divided into four parts.

1.1. Complex Thermal Behavior

Heat transfer mechanisms including convection, radiation and conduction have a significant role on the process behavior. Convection and radiation fluxes dissipate heat significantly through the workpieces to the surrounding environment, while conduction heat flux occurs between the workpieces and the support.

1.2. Non-Linear Behavior and Localized Nature

The mechanical behavior during FSW is non-linear due to the high strain rates and visco-plastic material. The strong non-linear region is limited to a small area and the remaining part of the model is mostly linear. However, the exact boundaries of the non-linear zone are not known a priori. Knowledge of strain rate is important for understanding the subsequent evolution of grain structure, and it serves as a basis for verification of various models as well.

1.3. Coupled Nature

The thermal and mechanical problems are strongly coupled. The mechanical effects coupled to the thermal ones include internal heat generation due to plastic deformations or viscous effects, heat transfer between contacting bodies, heat generation due to friction, etc. The thermal effects are also coupled to the mechanical ones; for instance, thermal expansion, temperature-dependent mechanical properties, temperature gradients in workpieces, etc. An adequate physical model of the welding process must account for all these phenomena including thermal, mechanical and coupling aspects.

1.4. Thermo-Mechanical Frictional Contact Nature

Thermo-mechanical frictional contact between the tool and the workpieces plays a crucial role. Interactions between the contacting bodies include impenetrability, frictional stresses, heat generation due to friction and thermal conduction at the contact interface. An adequate physical model of the FSW process must properly account for all those phenomena.

2. Numerical Model

The numerical simulation of the FSW process by the Finite Element Method (FEM) has many complex and challenging aspects that are difficult to deal with. The welding process is described by the momentum and energy balance equations governing the coupled thermo-mechanical problem. Both governing equations are non-linear and this has important implications upon the complexity of the numerical model. Consequently, a robust and efficient numerical strategy is crucial for solving such highly non-linear coupled FE equations. Numerical simulation of the FSW process can be carried out at a local or global level [1,2]. In local level analysis, the focus of the simulation is the Heat Affected Zone (HAZ). The simulation is intended to compute the heat power generated either by visco-plastic dissipation or by friction at the contact interface. At this level, the relevant process phenomena are the relationship between welding parameters, the contact mechanisms in terms of applied normal pressure and friction coefficient, the setting geometry, the material flow within the HAZ, its size and the corresponding consequences on the microstructure evolution, etc. A simulation carried out at global level studies the entire component to be welded. In this case, a moving heat power source is applied to a control volume representing the actual HAZ at each time-step of the analysis. The effects induced by the welding process on the structural behavior, such as distortions, residual stresses or weaknesses along the welding line, are the target of this kind of study. The challenging issues in numerical modeling of the FSW process are divided into the following seven parts.

2.1. Mechanical Problem

The mechanical problem is governed by the momentum balance equation. A quasi-static mechanical analysis can be assumed as the inertia effects in welding processes are negligible due to the high viscosity characterization. At local level, the volumetric changes are found to be negligible, and incompressibility can be assumed. To deal with the incompressible behavior, a very convenient and common choice is to describe the formulation splitting the stress tensor into its deviatoric and volumetric parts. Dealing with the incompressible limit requires the use of mixed velocity-pressure interpolations. The problem suffers from instability if the standard Galerkin FE formulation is used, unless compatible spaces for the pressure and the velocity fields are selected (LBB stability condition). Due to this, pressure instabilities appear if equal velocity-pressure interpolations are used. Thus, the challenging issue of pressure stabilization rises up [1–3,6]. The welding process is characterized by very high strain rates as well as a wide temperature range going from the environmental temperature to the melting point. Hence, the constitutive laws adopted should depend on both variables. At typical welding temperatures, the large strain deformation is mainly visco-plastic. Depending on the scope of the analysis, rigid-visco-plastic or elasto-visco-plastic constitutive models can be used. Not only the prediction of the temperature evolution, but the accurate residual stress evaluation field generated during the process is the objective of the FSW simulation. The selected constitutive model must appropriately define the material behavior and has to be calibrated by the temperature evolution. The challenge arises from the extremely non-linear behavior of these constitutive models and, therefore, from the numerical point of view, a special treatment is obligatory. Moreover, the localized large strain rates usually involved in FSW processes make the problem even more complex.

2.2. Thermal Problem

The thermal problem is defined by the energy balance equation. In FSW simulation, the plastic dissipation term appearing in the energy equation has a critical role on the process behavior and it is the main source of internal heat generation. The definition of the heat source is one of the key points when studying the welding process. In global level simulations, the mesh density used to discretize the geometry is not usually fine enough to define the welding pool shape or a non-uniform heat source. This is only done if the simulation of the welding pool is the objective itself (local level analysis). If the global structure is considered (global level analysis), the size of the heat source is of the same dimension than the element size generally used for a thermo-mechanical analysis. Therefore, in a global level analysis the resulting mesh density is usually too coarse to represent the actual shape of the heat source. Depending on the kinematic framework used to describe the formulation of the coupled thermo-mechanical problem, a convective term might appear in the thermal governing equations. Therefore, convection instabilities of the temperature appear for convection dominated problems [3,6]. It is well known that in diffusion dominated problems, the solution is stable. However, in convection dominated problems, the stabilizing effect of the diffusion term becomes insufficient and oscillations appear in the temperature field. The threshold between stable and unstable solutions is usually expressed in terms of the Peclet number.

2.3. Kinematic Framework

Establishing an appropriate kinematic framework for the simulation of FSW processes is a key issue. If the welding process is studied at global level, the use of a Lagrangian framework is an appropriate choice for the description of the problem. The Lagrangian reference frame allows easy tracking of free surfaces and interfaces between different materials. In a local simulation, the main focus of the simulation is the HAZ where the use of a Lagrangian framework is not always advantageous. In the HAZ, the large distortions would require continuous re-meshing. The alternative is to use Eulerian or Arbitrary Lagrangian Eulerian (ALE) methods. The Eulerian formulation facilitates the treatment of large distortions in the fluid motion. Its handicap is the difficulty to follow free surfaces and interfaces between different materials or different media. An Arbitrary Lagrangian Eulerian (ALE) formulation is particularly useful in flow problems involving large distortions in the presence of mobile and deforming boundaries. In the simulation of FSW, it is adroit to introduce an apropos kinematic framework for the description of different parts of the computational domain [4,6]. Despite the efficiency of the idea, the mesh moving strategy and the treatment of the domains' interaction are challenging.

2.4. Thermo-Mechanical Frictional Contact Problem

The computational modeling of the thermo-mechanical frictional contact between the tool and workpieces is a key issue in the numerical simulation of the FSW process [1,2,6]. The computational model must accurately deal with contact impenetrability, frictional behavior, heat generated by friction and heat transfer due to thermal contact at the contact interface. Penalty-based methods, such as the penalty method or the Uzawa's version of the augmented Lagrangian method, Lagrange multipliers or direct elimination methods, can be used to model the mechanical frictional contact interaction. Within the framework of a fluid mechanics approach, a Norton thermo-frictional contact model can be used to compute the tangential component of the traction vector at the contact interface in terms of the variation of the relative slip velocity. The heat flux generated by friction at the contact interface between the tool and the workpieces can be split into two parts, that is, a part absorbed by the tool and a part absorbed by the workpieces, where the amount of heat absorbed by the tool and the workpieces depends on the thermal diffusivity of the two materials in contact. Alternatively, as a limit case, full stick thermo-mechanical contact conditions between the tool and the workpieces can be also considered.

In this case, the temperature and velocity fields are continuous through the contact interface between the tool and the workpieces.

2.5. Coupled Problem

The numerical solution of the coupled thermo-mechanical problem involves the transformation of an infinite dimensional transient system into a sequence of discrete non-linear algebraic problems [6]. This is achieved by means of the FE spatial discretization procedure, a time-marching scheme for the advancement of the primary nodal variables and a time integration algorithm to update the internal variables of the constitutive equations. Regarding the time-stepping schemes, two types of strategies can be applied to the solution of the coupled thermo-mechanical problems. The first possibility is to use a monolithic (simultaneous) time-stepping algorithm which solves both the mechanical and the thermal problems together. It advances all the primary nodal variables of the problem simultaneously. The main advantage of this method is that it enables stability and convergence of the whole coupled problem. However, in simultaneous solution procedures, the time-step as well as time-stepping algorithm has to be equal for all subproblems, which may be inefficient if different time scales are involved in the thermal and the mechanical problem. Another important disadvantage is the considerably high computational effort required to solve the monolithic algebraic system and the necessity to develop software and solution methods specifically for each coupled problem. A second possibility is a staggered algorithm (block-iterative or fractional-step), where the two sub-problems are solved sequentially. Usually, a staggered solution, arising from an operator split and a product formula algorithm (PFA), yields superior computational efficiency. Staggered solutions are based on an operator split, applied to the coupled system of non-linear ordinary differential equations, and a product formula algorithm, which, within the framework of classical fractional step methods, leads to a splitting of the original monolithic problem into two smaller and better conditioned sub-problems. This leads to the partition of the original problem into smaller and typically symmetric (physical) subproblems. After this, the use of different standard time-stepping algorithms developed for the uncoupled sub-problems is straightforward, and it is possible to take advantage of the different time scales involved. The major drawback of these methods is the possible loss of accuracy and stability. However, it is possible to obtain unconditionally stable schemes using this approach, providing that the operator split preserves the underlying dissipative structure of the original problem.

2.6. Particle Tracing

One of the main issues in the study of FSW at local level is the heat generation. The generated heat must be enough to allow for the material to flow and to obtain a deep HAZ. Insufficient heat forms voids as the material is not softened enough to flow properly. The visualization of the material flow is a very useful tool to understand its behavior during the weld. It can be used to investigate the appropriate process parameters to create a qualified joint. However, following the position of the material during the welding process is not an easy task, neither experimentally (needs metallographic tools) or numerically. This is why establishing a numerical method for the visualization of the material trajectory in order to gain insight to the HAZ and the material penetration within the thickness of the workpieces is one of the key issues of the numerical simulation. Particle tracing is a method used to simulate the motion of material points, following their positions at each time-step of the analysis [5]. In the Lagrangian framework the trajectories are given by the displacement field. When using Eulerian and ALE framework the solution does not give directly information about the material position. However, the velocity field obtained can be integrated to get an insight of the extent of material mixing during the weld. Integration of the velocity field is proposed at post-process level to follow the material motion. An appropriate time integration method for the solution of the ODE in order to track the particles is needed. Moreover, a search algorithm must be executed to find the position of the material points if Eulerian or ALE meshes are used.

2.7. Residual Stresses

Generally, FSW yields fine microstructures, absence of cracking, low residual distortion, and no loss of alloying elements. Nevertheless, as in the traditional fusion welds, a softened HAZ and a tensile residual stress field appear. Although the residual stresses and distortion are smaller in comparison with those of traditional fusion welding, they cannot be ignored, especially when welding thin plates of large size. In the local level analysis, the focus of the study is the HAZ and a visco-plastic model is used to characterize the material behavior. Elastic stresses are neglected, and thus, the calculation of residual stresses is not possible. However, at global level, the residual stresses are one of the main outcomes of the process simulation using an elasto-visco-plastic constitutive model. The use of a local-global coupling strategy has been proposed as a method to obtain the residual stress field, as this a challenging issue [2].

Conflicts of Interest: The authors declare no conflicts of interest.

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