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Modeling heat transfer during friction stir welding using a meshless particle method

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ABSTRACT

Modeling heat transfer during friction stir welding (FSW) process is crucial for understanding welding mechanism and optimizing process parameters. Since heat transfer is usually accompanied with the material flow in FSW, the meshless method, which can easily treat large deformation in a Lagrangian framework, is promising for FSW modeling. In this paper, we develop a meshless particle method for the analysis of transient heat transfer during FSW process. In the developed method, a heat source model based on sticking friction is implemented to describe the heat generation of FSW. A particle approximation with first-order consistency is employed to discretize the governing equation of heat transfer. A penalty method is proposed to impose different thermal boundary conditions, and a smoothing algorithm is introduced to enhance numerical stability. Two examples are firstly given to verify the accuracy and parametric effect of the meshless particle method. The method is then used to simulate heat transfer during FSW of 12.7 mm-thick Al6061-T6 plates. The calculated temperature distributions are presented and compared with those computed by FEM. The obtained thermal cycles are found to be in good agreement with those obtained from experiments. The validated model of FSW of Al6061-T6 plates is then employed to predict the maximum temperature, heat generation rate and torque for various welding parameters and tool dimensions.

1. Introduction

Friction stir welding (FSW) [1] is a renowned solid-state joining technology. Understanding of heat transfer during the FSW process is of great importance to FSW researchers because it largely determines the weld performance. Experimental measurement has been extensively used to study the thermal process of FSW. However, it suffers from several limitations, such as difficulties in testing temperature of stir zone and limited data of the temperature field. Alternatively, numerical modeling is an effective avenue in understanding such thermal process. In this regard, many numerical simulations [2–13] have been carried out to explore the temperature distribution and other physics that is involved in FSW. Various approaches including finite element method (FEM) [2–4], finite difference method [5–7] and meshless methods [8–13] have been utilized in these numerical simulations. Owing to the flexibility in space discretization and the capability of modeling large deformations in a Lagrangian framework, the meshless method appears as a promising tool in FSW modeling, especially in the coupled thermal–mechanical analysis of FSW for predicting temperature distribution and material flow simultaneously.

Meshless methods use points without connectivity for calculation. They provide advantages over FEM in many aspects, e.g., could easily treat complex geometries and incorporate adaptivity, could handle large deformation and discontinuity, and have good accuracy and high convergence rate. Currently, there are a number of meshless methods proposed, such as smoothed particle hydrodynamics (SPH) method [14], element-free Galerkin (EFG) method [15], reproducing kernel particle method (RKPM) [16], meshless local Petrov–Galerkin (MLPG) method [17] and point interpolation method [18]. These methods have been widely applied to fluid and solid mechanics problems, and are especially popular for problems involving large displacements and deformations like fluid flow [19], impact [20] and explosion [21]. In heat transfer field, meshless methods have also been extensively investigated and used. A. Singh, I.V. Singh and Prakash [22–25] have done important fundamental works on EFG method for heat transfer application. Singh, Tanaka and Endo [26–32] made a number of contributions

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Nomenclature

a_0, a_1, a_2, a_3	polynomial coefficients for material property
c	specific heat
C_f	fraction of heat flowing into workpiece
e	weighted error function
e_s, e_g	maximum relative error and global relative error of temperature, respectively
f, f_i, $\hat{f}_i$	function, function value and estimated function value at particle i, respectively
F_f	frictional stress
h_1	convective heat transfer coefficient for sides and top surface of workpiece
h_2	convective heat transfer coefficient for bottom surface of workpiece
h_p	height of tool pin
l	smoothing length
M	torque exerted on tool
n	rotational speed of tool
$\mathbf{n}$	unit outward normal vector
N	number of neighboring particles for a particle
N_b	number of boundary conditions for a particle
P_s, P_b, P_{sh}	heat generation rate of side and bottom surface of tool pin and shoulder, respectively
q	welding heat input
q_{sh}	surface heat flux from shoulder
Q	volumetric heat source, $Q = Q_s + Q_b$
Q_s, Q_b	volumetric heat source from side and bottom surface of tool pin, respectively
r	distance from a given point to symmetric axis of tool
r_p, r_{sh}	radius of tool pin and shoulder, respectively
t, t_0	time and initial time, respectively
t_s, t_b	radial distance for determining Q_s and axial distance for determining Q_b, respectively
T, T_{max}, T_a, T_s	temperature, maximum temperature of workpiece, ambient temperature and temperature on surfaces of workpiece, respectively
v_w	welding speed
W_{ij}	smoothing function
x, y, z	coordinate components
α_p	penalty parameter for enforcement of boundary conditions
β	stable time-step coefficient
ε	smoothing parameter
λ, λ_W, λ_T	thermal conductivity, thermal conductivity of workpiece and thermal conductivity of tool, respectively
ρ	density
σ_y	yield stress
τ	maximum shear stress for yielding
ω	angular velocity of tool
Δt	time step

to thermal analysis of composites especially carbon nanotube (CNT) composites based on EFG method. Wu and Tao [33] applied MLPG method to 2D steady-state heat transfer problems with irregular complex domain. Thakur et al. [34,35] employed MLPG method to solve nonlinear heat transfer in irregular domains and phase change problems. Tian and Rao [36] proposed a MLPG method for solving steady-state nonlinear heat transfer problems with boundary conditions including heat flux, convection and radiation.

In recent years, a few meshless methods including natural element method (NEM) [8], adaptive EFG method [9] and SPH method [10–13] have been extended to model FSW process. Among these meshless methods, SPH method is the most popular one. This mainly benefits from its attractive features. Firstly, SPH method is a truly meshless method, which avoids numerical integration and the use of background meshes. Secondly, particle approximation for function and its derivatives in SPH method can be simply achieved by a summation over particles. Moreover, SPH method is easy to be implemented for high dimensional problems and to incorporate models for complex physics. However, SPH method also has its own deficiencies. One is the relatively low accuracy for particle approximation, especially for boundary particles and non-uniform particles. To overcome this problem, different modified methods have been proposed, such as RKPM [16], corrected smoothed particle method (CSPM) [37], finite particle method (FPM) [38], modified smoothed particle hydrodynamics (MSPH) [39] and symmetric smoothed particle hydrodynamics (SSPH) [40]. Among these modifications, SSPH shows attractive characteristics, which include the symmetry of matrix, no requirement of differentiating kernel function and the approximation of function and its derivatives obtained simultaneously. Another deficiency of SPH method is the inconvenience in dealing with boundary conditions. Very few studies have highlighted the enforcement of boundary conditions for SPH modeling of heat transfer. Monaghan et al. [41] discussed the treatment of temperature-specified boundaries and adiabatic boundaries (no need of treatment). Jeong et al. [42] presented a method, which needs the use of ghost particles, to implement temperature-specified and heat flux-specified boundary conditions.

In this paper, we develop a meshless particle method to simulate the nonlinear transient heat transfer process of FSW. The method has the advantages of being truly meshless and easy implementation like SPH. Meanwhile, it has an improved particle approximation and an adequate method to treat various thermal boundary conditions conveniently. Specifically, the present method uses a set of particles without any connectivity to represent a problem domain, and directly enforces governing equations at each particle. It employs a particle approximation having first-order consistency to accurately approximate the field function and its derivatives. A penalty method, which avoids the use of ghost particles, is proposed to deal with all kinds of thermal boundary conditions involved in FSW process. A smoothing algorithm based on temperature change rate is introduced to ensure numerical stability. A heat source model based on sticking friction is derived and implemented to describe the heat generation in FSW process. The developed meshless particle method is finally applied to the simulation of temperature distributions during FSW of Al6061-T6 plates. It is worth mentioning that similar meshless framework has also been used in our previous work [43], which has focused on the modeling of tungsten inert gas (TIG) welding of stainless steel, while this work proposes its first-time application to the modeling of FSW. Also, in comparison with our previous work [43], the current method has several new features and improvements, such as new treatment of boundary condition, modified smoothing algorithm and simplified particle approximation. Moreover, a more complex heat source model for FSW modeling is incorporated.

The rest of the paper is organized as follows. Section 2 describes the mathematical model for heat transfer during FSW process. Section 3 details the formulation of the meshless particle method. Section 4 presents two test cases to verify the accuracy and parametric effect of the method. Section 5 gives the numerical