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A non-ordinary state-based peridynamics formulation for thermoplastic fracture

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ABSTRACT

In this study, a three-dimensional (3D) non-ordinary state-based peridynamics (NOSB-PD) formulation for thermomechanical brittle and ductile fracture is presented. The Johnson–Cook (JC) constitutive and damage model is used to taken into account plastic hardening, thermal softening and fracture. The formulation is validated by considering two benchmark examples: 1) The Taylor-bar impact and 2) the Kalthoff–Winkler tests. The results show good agreements between the numerical simulations and the experimental results.

1. Introduction

For numerous years, materials and structures with thermomechanical characteristic have attracted significant interest. The presence of defects, such as notches and voids, reduce its functionality because of initiation and propagation of cracks. Despite the existence of many approaches for numerical simulation of crack initiation and propagation in local theory of continuum mechanics (e.g. extended finite element [1,2,58,59], meshfree [3–9,60–62], phantom-node [10–12], XIGA [13,14,63–68] and remeshing techniques [15,16,69–71]), it is still a major challenge within these frameworks. From the mathematical point of view, they are based on partial differential equations in which spatial derivatives fail whenever a discontinuity appears in a body [17]. The domain of the applicability of classical field theories is intimately connected to the length and time scales. If L denotes the external characteristic length (e.g. crack length, wavelength) and l the internal characteristic length (e.g. granular distance, lattice parameter), then in the region L/l » 1, classical field theories predict sufficiently accurate results. On the other hand, when L/l~1, local theories fail. In dynamics, there will be a similar scale T/t where T is the external characteristic time (e.g. the time scale of the applied load) and t is the internal characteristic time (e.g. the time scale of signal transmission from one molecule to the next). Again, classical theories fail when T/t~1. Hence, the physical phenomenon in space and time scales requires nonlocality scaled by L/l and T/t[18]. Nonlocal continuum theory can be used to overcome the above mathematical challenge of the local theories. The concept of nonlocality is inherent in solid state physics where the nonlocal attractions of atoms are prevalent. Here, the material is considered to consist of discrete atoms connected by distant forces from other neighboring atoms [18].

A nonlocal formulation based on integro-differential equations called peridynamics (PD) was introduced by Silling [19]. The PD theory reformulates the equation of motion such that no spatial derivatives are required. In the PD theory, a continuous body consists of material points interacting in a nonlocal manner. Hence, PD can be considered as a nonlocal meshless method with advantages in problems involving large deformation where mesh-based methods fail. The PD theory permits modeling bodies with discontinuities

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and its propagation. Fracture is the natural outcome of the PD simulation and damage is a part of the material response. The original version of PD [19] later was named as the bond-based peridynamics (BB-PD) theory. The state-based PD (SB-PD) theory [20] is a generalization of the BB-PD theory (for limitations of the BB-PD see Ref. [20]). The SB-PD has two types: ordinary state-based (OSB) and non-ordinary state-based (NOSB) (for details about the differences see the definition 8.4 in Ref. [20]). To establish a SB-PD, the material-dependent part has been rewritten, introducing a mathematical object called a “force-vector state” that is in some ways similar to the traditional stress tensor of classical continuum mechanics. Therefore, the traditional constitutive models can be incorporated into the SB-PD model. For instance, Mitchell [21] implemented an elastic-perfect plasticity constitutive model into the OSB-PD theory. Similar contribution the OSB-PD includes in the work by Warren et al. [22] for incorporating the elasto-plastic linear hardening constitutive model. In the NOSB-PD theory, Foster et al. [23] extended viscoplastic material model and Tupek et al. [24] incorporated the modified Johnson–Cook constitutive model that does not contain the temperature effect.

The PD theory was extended successfully to heat diffusion problems. Kilic and Madenci [25] used the BB-PD theory for prediction of thermally driven crack propagation patterns in quenched glass plates containing single or multiple pre-existing cracks due to thermal loading. Bobaru and Duangpanya [26] formulated a one-dimensional BB-PD theory for the heat conduction equation and also extended it to solve two-dimensional problems with discontinuities [27]. Kilic and Madenci [28] proposed a BB-PD formulation for uncoupled thermomechanical problems. They included the thermal term in the response function of the PD interactions. They introduced a multi-dimensional PD heat conduction equation and considered domains with discontinuities such as insulated cracks. Gerstle et al. [29] developed a BB-PD model for electro-migration that accounts for one-dimensional heat conduction problems. Oterkus et al. [30] derived a SB-PD model of the heat conduction equation based on the Lagrangian formalism. Also, Oterkus et al. [31] extended it for analysis of 2D problems. Agwai [32] formulated an OSB-PD formulation for fully coupled thermoelasticity using the conservation of thermal and mechanical energy along with the free-energy function. She also derived a dimensionless BB-PD form of the coupled equations using the OSB-PD formulation and applied it to solve one dimensional examples. Oterkus et al. [33] extended it to solve 2D and 3D problems.

To our best knowledge, no attempt has been made to develop the NOSB-PD theory for ductile fracture analysis of thermoplasticity problems. Hence, the main purpose and motivation of this paper is to extend a 3D thermomechanical model to a NOSB-PD framework to use its ability to deal with ductile fracture analysis. One of the main feature of ductile fracture in thermomechanical process is its dissipative character. The large amount of heat generated by plastic work around the crack tip area causes thermal softening, shear banding and thermal damage [34]. Among the most popular constitutive models for ductile fracture accounting for plastic hardening, thermal softening, strain rate effects and ductile damage is the Johnson–Cook model. For adiabatic heating, the thermomechanical coupling can be modeled only through the inelastic heat fraction which indicates the plastic work fraction converted into heat [3]. We will restrict our attention to thermoplasticity problems subjected to adiabatic heating and it is not our purpose to solve the fully coupled thermomechanical equations. We adopt the JC model for constitutive modeling and for damage assessment. We present the detailed implementation of the NOSB-PD for thermoplasticity. The Taylor-bar impact test is exploited to validate the proposed method. Another validation experiment is the Kalthoff–Winkler experiment.

The remaining of this paper is organized as follows: Section 2 provides the JC constitutive and damage model. In Section 3, the concept of the PD theory and also the NOSB-PD formulation of the thermomechanical problems are presented. The numerical verification and results are presented and compared against experimental data in Section 4. Finally, some concluding remarks are summarized.

2. Johnson–Cook model

2.1. Johnson–Cook constitutive model

In dynamic applications such as high velocity impact problems, the effects of strain hardening, thermal softening and strain rate are important. The Johnson–Cook constitutive model [35,36] accounts for those effects. The von-Mises flow stress from the JC constitutive model is given by

$$S=[A+B\varepsilon_p^n][1+C\ln\dot{\varepsilon}_p^*][1-T^{*m}],\quad \dot{\varepsilon}_p^*=\frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_{p0}},\tag{1}$$

where ε_p is the equivalent plastic strain, A is the yield stress, B and n are strain hardening constants, C is the strain rate constant, m is the temperature softening exponent parameter, $\dot{\varepsilon}_p^*$ is the dimensionless plastic strain rate, $\dot{\varepsilon}_p$ and $\dot{\varepsilon}_{p0}=1.0s^{-1}$ are the plastic strain rate and its reference value, respectively and T^* is the homologous temperature defined as

$$T^*=\frac{T-T_0}{T_m-T_0},\tag{2}$$

in which T, T_0 and T_m are the current, reference (room) and melting temperatures, respectively.

Camacho and Ortiz [37] modified the von-Mises flow stress of the JC constitutive model to avoid unwanted effects for $\dot{\varepsilon}_p^*<1$. Therefore,

$$S=[A+B\varepsilon_p^n][1+\dot{\varepsilon}_p^*]^C[1-T^{*m}].\tag{3}$$

2.2. Johnson–Cook damage model

The Johnson–Cook damage model relates the accumulative damage D to an equivalent plastic strain increment $\Delta\varepsilon_p$ as [36].

$$D=\sum_{k=1}^{nt}\frac{\Delta\varepsilon_p}{\varepsilon^f},\tag{4}$$

where nt is the number of time steps in the time discretization procedure and ε^f is the fracture strain defined as a function of the homologous temperature, strain rate and pressure as [36,38]:

$$\varepsilon^f=[D_1+D_2\exp(D_3\sigma^*)][1+D_4\ln\dot{\varepsilon}_p^*][1+D_5T^*],\quad \sigma^*=\frac{\sigma_m}{S}\le 1.5,\tag{5}$$

where $D_1,\ldots,D_5$ are material constants, σ_m = trace($\boldsymbol{\sigma}$)/3 is the hydrostatic pressure obtained from the Cauchy stress tensor $\boldsymbol{\sigma}$ and σ^* is the stress triaxiality ratio. When $\sigma^*>1.5$, a linear relationship for the fracture strain ε^f was proposed in Ref. [36]. The $\sigma_{spall}^*=\sigma_{spall}/S$ is the dimensionless spall fracture computed from the spall fracture and the current value of the von-Mises stress. The first bracket of Eq. (5) reveals that the fracture strain decreases as the hydro-