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A stabilized non-ordinary state-based peridynamics for the nonlocal ductile material failure analysis in metal machining process

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Abstract

This paper presents a non-ordinary state-based peridynamic formulation that can be applied to the metal machining analysis. The new formulation is first derived by utilizing the technique of mixed local/nonlocal gradient approximations to enforce the contact and essential boundary conditions associated in modeling the machining process. A stabilized peridynamic force vector state is then introduced to suppress the zero-energy modes which show up as the result of particle integration of the state-based peridynamic formulation. The introduction of the stabilized peridynamic force vector state eliminates the need of an estimation of the force–spring-like bond forces and leads to a consistent computation of peridynamic equations of motion using a general constitutive model. Finally, a continuum damage model is incorporated into the present state-based peridynamic formulation together with a decomposed stabilized approximate deformation gradient based on a neighbor particle reconstruction scheme to model the ductile metal failure and to maintain a well-defined geometric mapping in finite deformation. Three numerical benchmarks are analyzed to demonstrate the effectiveness and regularization of the present method for simulating the metal machining process.

Keywords: State-based peridynamics; Mixed local/nonlocal approximation; Stabilization; Machining

1. Introduction

Metal machining including the shaping, turning, drilling and milling is a manufacturing process of removing the undesired metal material from a work-piece. US industries annually spend $60 billion [1] performing metal removal operations because the vast majority of manufactured products such as casting or forging require machining at some stage in their production. Thus machining undoubtedly is one of the important procedures in the basic manufacturing process [2]. Numerical modeling of the machining process in manufacturing problems has been the continuous focus in computational mechanics for many decades. Despite a lot of research [3,4] done, numerical prediction of the physics of machining process is still incomplete and remains challenging. The main computational difficulty emanates from a lack of robust numerical methodology permitting an accurate presentation of the material failure/separation during

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the metal removal process. Peridynamics [5,12] is a new continuum theory that describes the material deformation by a nonlocal approach. Unlike the continuum weakly or strictly nonlocal models [6–8] where the spatial derivatives appearing in the weak form of partial differential equations do not exist along the material failure surfaces, the peridynamic model does not rely on the spatial derivatives. This property of the peridynamic theory allows it to include the displacement discontinuities in a continuum body without explicitly modeling the failure surfaces. Compared to the most popular approaches that introduce discontinuities into the displacement field by means of enriching the basis functions [9], peridynamics does not require sophisticated bookkeeping of the degrees of freedom or jump conditions in tracking the moving discontinuities. This unique feature of peridynamics offers significant advantages over other advanced numerical methods for the metal machining simulations.

The bond-based peridynamics [5] is the first peridynamic model developed by Silling to describe the formation of discontinuities in brittle materials. Silling [10] introduced the Prototype Microelastic Brittle (PMB) model which considers a pairwise force function that depends linearly on the bond stretch. A maximum bond-stretch criterion [10] was also proposed by them for the propagation of cracks in brittle materials. The maximum bond stretch is linked to the fracture energy release rate with the assumption that the crack surface is away from the geometrical boundary and Poisson's ratio is fixed at one-quarter in the three-dimensional case. The surface effect was considered by Madenci and Oterkus [11] with the introduction of ellipsoidal surface correction factors in the bond-based peridynamic computation. On the other hand, the restriction of fixed Poisson's ratio in the bond-based peridynamics is due to the hypothesis that each peridynamic bond responds independently to all the others in the isotropic linear elastic solids. To address this lack of generality, the ordinary and non-ordinary state-based peridynamics [12] was developed. While the ordinary state-based peridynamics restricts the bond force to be parallel to the bond vector, the non-ordinary state-based peridynamics admits the bonds to carry force vector states in all directions which make it possible to incorporate general constitutive models. The state-based peridynamics is a generalization of the bond-based peridynamic framework that allows the response of a given material point to depend on the collective deformation of all bonds that are within a finite distance (or domain of influence). In other words, the heterogeneous bond force is volume-dependent and incorporates the surrounding interacting material points. This leads to a release of the restriction of fixed Poisson's ratio in the bond-based peridynamics applications. It has been shown [13] that the non-ordinary state-based peridynamics is closely related to the reproducing kernel particle method [14] with synchronized derivatives [15].

Although the state-based peridynamics has been applied to a wide range of applications [16,17], limited research work [18] was reported in the area of material failure/separation analysis, especially the manufacturing problems. One of the bottlenecks is due to its non-trivial treatment of boundary conditions. Since the equations of motion in peridynamics utilize an integral form as opposed to the partial differential equations in the classical continuum mechanics, the enforcement of kinematic constraints in peridynamics cannot follow the standard way as in the classical continuum theory. Because of that, the peridynamic formulation demands special numerical treatments similar to those in the other particle/meshfree methods [19–21] to enforce the boundary conditions. Representatives include the incorporation of ghost particles [22], the modification of particle volume integration near the boundary [23], the combination with finite element method using a sub-modeling technique [24], the method of interface elements [25] and the introduction of a localized kernel approximation [26]. Lastly, a corrected numerical scheme [27] was presented to improve the numerical treatments of kinematic constraints in the state-based peridynamics. The work in [27] also led to a new coupling scheme between the state-based peridynamics and the Galerkin-type of numerical methods such as the finite element method. In addition to the difficulty in enforcing the boundary conditions, the non-ordinary state-based peridynamics also experiences the spurious or zero-energy modes [18] in the deformation field when the size of horizon region is either too large or too small. The presence of spurious or zero-energy modes in the non-ordinary state-based peridynamics resembles the appearance of unstable or hourglass modes observed in the weak form integration of Galerkin formulation using the central-difference-like formula and it is required to be suppressed. Several control methods of zero-energy modes have been developed [28] for the non-ordinary state-based peridynamic analysis. The method supplemented with the interconnected linear springs [28] is a simple approach adding the spring forces between particle bonds for stabilization. The method based on the penalty approach [29] introduces the hourglass vectors predicted based on the smoothed deformation gradients to obtain the stabilized deformation field. The method using average displacement state [28] provides a smoothing of hourglass modes using the peridynamic influence function. The hourglass force vector state based on the smoothed displacement state is then introduced to the peridynamic force vector state through a force–spring relationship. Nevertheless, a common feature of those hourglass