Composite Structures 166 (2017) 193–201

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Meshfree formulation for modelling of orthogonal cutting of composites

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ARTICLE INFO

Article history:
Received 4 October 2016
Revised 8 December 2016
Accepted 11 January 2017
Available online 19 January 2017

Keywords:
Meshfree
Element-Free Galerkin
Orthogonal cutting
Modelling of machining
Unidirectional composites

ABSTRACT

The Element-Free Galerkin method (EFG) is a prominent member of the meshfree methods family. In this work, EFG is utilised to simulate the orthogonal cutting process of unidirectional composites. The mathematical model is derived from the weak form of the momentum conservation equation with frictional contact constraints based on penalty method. Spatial discretisation using moving least squares shape functions are used. The onset and progression of damage are predicted by two stress-based failure criteria. Full Newton Raphson solver is used to solve the non-linear system equations iteratively. Numerical experiments investigating the effect of rake angle and fibre orientation are conducted. Cutting forces are compared against experiments and finite element simulations available in literature. Simulations show that the meshfree model is capable of predicting cutting forces as a function of the fibre orientation. Sensitivity analysis is conducted to investigate the effect of important meshfree parameters such as the domain of influence and weight function on forces. One of the strongest advantages of the proposed model is the simple and automatic set up process, as meshing for domain discretisation is not required.

1. Introduction

Global demand for glass fibre reinforced plastic (GFRP) and carbon fibre reinforced plastic (CFRP) is steadily growing [1,2], with total projected market worth of B$105.26 by 2021 [3]. Composites are considered difficult-to-machine materials [4]. This is mainly due to their strong anisotropy, abrasive nature of reinforcement, different behaviour of constituent materials under machining conditions and the complex failure mechanisms [4]. Modelling of machining is utilised to gain fundamental understanding of the machining process and to reduce costly trial and error at the floor shop. Modelling of machining can be analytical, numerical or empirical. The current practice of modelling of composites machining was reviewed in [5]. Extensive research was conducted on numerical modelling of machining composites. The bulk of the research utilised the finite element method (FEM). Interested readers can refer to [4,6] to review the state of the art in numerical modelling of machining composites.

Orthogonal cutting process is widely used in modelling of machining since it is 2D process and is capable of revealing the basic mechanisms in material removal [7]. The orthogonal cutting process is usually simulated either as a steady state process or as transient process. In the former, the dynamic effects are not considered and the process is assumed quasi-static. This enables the use of implicit solving techniques like Newton Raphson, which is more suitable for cutting at low speeds. The second approach accounts for the dynamic effects and is more suitable for machining at higher speeds. Dynamic studies usually utilise explicit solving techniques such as the central difference method. Studies that used the steady state approach include [8–13]. Some studies that adopted the transient approach include [14–20].

Material modelling is one of the crucial aspects in modelling of machining composites. Two main approaches have been used, macromechanical modelling, and micromechanical modelling. The former assumes the material to be one equivalent phase and sometimes called Equivalent Homogeneous Material. The micromechanical approach models fibres and matrix separately. Most of the studies utilising macromechanical approach used linear elastic material model [8,9,11,13]. However, Zenia [20,21] used a combined elasto-plastic model with isotropic hardening and without plastic flow in the principle fibre direction.

Material failure and chip formation are important features of the machining simulation. Material failure is governed by composite failure criteria. Different studies used various failure criteria, such as Tsai-Hill [8,10,14], maximum stress [10,11], Hashin [11,15,17]. Some studies [8–10] combined two failure mechanisms, primary failure for the onset of chip formation and a secondary failure for the progressive failure and completion of chip formation. The progressive failure was modelled through stiffness

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http://dx.doi.org/10.1016/j.compstruct.2017.01.021
0263-8223/

degradation concept [11] or continuum damage mechanics approach [15–17] .

In addition to FEM, meshfree (meshless) methods provide a powerful numerical analysis tool. They have been developed to address some of the disadvantages of FEM such as burdensome mesh generation. Currently there are several methods under the umbrella of meshfree methods such as: Smoothed particle hydrodynamics (SPH), Element Free Galerkin (EFG), HP clouds, reproducing kernel particle methods, radial point interpolation method and others. Machining of metals have been studied using some meshfree methods such as: Material Point Method [22], finite pointset method [23] and smoothed particle hydrodynamics [24–28]. Iliescu et al. [29], developed a model for machining composites utilising the discrete element method. The workpiece was modelled as discrete particles with connections. The fibres were modelled as lines of particles closely joint and separated from the neighbouring lines. This allowed investigating the chip formation in comparison with high speed videos at different orientations. The method was able to qualitatively capture the basic failure mechanisms. The accuracy of the cutting force prediction was within ±50% of the experimental values. The Element-Free Galerkin Method (EFG) is a member of the meshfree methods family. The EFG was conceived in Belytschko's seminal paper in 1994 [30]. In the subsequent years, the method undergone many advances and was extended to many engineering applications such as fracture mechanics [31,32], heat transfer [33,34], fluid flow calculations [35], metal forming [36], shells [37,38], plates and laminates [39,40] and functionally graded materials [41] to name a few. This was due to the suitability of this method in dealing with moving discontinuities, large deformations, and ease of adaptive procedure [42]. However, to the authors' best knowledge, the EFG has not been extended to machining operations, be it metals or composites.

Therefore, this paper aims at simulating the orthogonal cutting process of unidirectional composites using the Element Free Galerkin Method with emphasis on cutting forces as a fundamental output of the model using the steady state approach. Theoretical formulation of the model will be presented first followed by numerical implementation aspects then the results are presented and discussed.

2. Governing equations

In this study, the workpiece is considered as a 2D domain Ω bounded by a boundary Γ governed by:

$$\mathbf{L}\cdot\boldsymbol{\sigma}+\mathbf{b}=\mathbf{0} \tag{1}$$

where $\mathbf{L}$ is a differential operator, $\boldsymbol{\sigma}$ is the stress tensor, $\mathbf{b}$ the body force. Eq. (1) is subject to displacement boundary conditions $\mathbf{u}(\mathbf{x})=\bar{\mathbf{u}}$ for $\mathbf{x}\in\Gamma_u$ and traction boundary conditions $\boldsymbol{\sigma}\cdot\mathbf{n}=\bar{\mathbf{t}}$ for $\mathbf{x}\in\Gamma_t$, where, $\bar{\mathbf{u}}$ is the prescribed displacement, $\mathbf{n}$ is the outward normal on Γ_t and $\bar{\mathbf{t}}$ is the prescribed traction along the traction boundary. By applying the variational principle and adding penalty term enforcing the displacement boundary conditions [43], the variation of stationary total potential energy for linear elastic materials can be obtained

$$\delta\Pi\equiv\int_{\Omega}(\mathbf{L}\delta\mathbf{u})^{T}\mathbf{D}(\mathbf{L}\mathbf{u})\,\mathrm{d}\Omega-\int_{\Omega}\delta\mathbf{u}^{T}\mathbf{b}\,\mathrm{d}\Omega-\int_{\Gamma_t}\delta\mathbf{u}^{T}\bar{\mathbf{t}}\,\mathrm{d}\Gamma-\int_{\Gamma_u}\delta(\mathbf{u}-\bar{\mathbf{u}})^{T}\alpha_u(\mathbf{u}-\bar{\mathbf{u}})\mathrm{d}\Gamma=0 \tag{2}$$

where α_u is a penalty parameter and $\mathbf{D}$ is the material coefficients matrix. Orthogonal cutting problem is a multibody problem where cutting tool and workpiece come into contact. As such, contact calculations need to be added to the model.

2.1. Frictional contact formulation using penalty method

Fig. 1 shows a generic case for two discretised bodies in contact. A common way to approach contact calculations is by assuming one body as master and the other as slave. When the slave body moves from configuration Ω_0 to configuration Ω, then the slave node (S) penetrates the master body in the segment M_1M_2 and contact is assumed to have taken place. The local coordinates are defined at the first point of the master segment with outward unit normal ($\mathbf{n}$) and in plane unit tangent ($\mathbf{t}$). As a result of the penetration, normal and tangential gap functions are defined as follows:

$$g_n=(\mathbf{u}^S-\mathbf{u}^{M_1})\cdot\mathbf{n} \tag{3}$$

$$g_t=(\mathbf{u}^S-\mathbf{u}^{M_1})\cdot\mathbf{t} \tag{4}$$

where $\mathbf{u}^S$ is the displacement of the slave node, and $\mathbf{u}^M$ is the displacement of the master node, $\mathbf{t}=\frac{\mathbf{x}_{M_2}-\mathbf{x}_{M_1}}{\|\mathbf{x}_{M_2}-\mathbf{x}_{M_1}\|}$ and $\mathbf{n}=\mathbf{t}_3\times\mathbf{t}$, $\mathbf{t}_3$ is the out-of-plane unit tangent.

Two basic contact conditions need to be satisfied at the contact boundary, the first is called the *impenetrability condition,* which states that the two bodies cannot occupy the same space at the same time. The second one is the negative traction condition, which states that the traction at the contact boundary should be compressive assuming no welding or adhesion occurs between the bodies. When the normal gap g_n is negative, the impenetrability condition is violated and contact occurs. The tangential slip expression in Eq. (4) represents the sliding movement of the slave node on the boundary of the master body. Using Coulomb friction law, we can distinguish between two cases: the first is when there is no relative motion between the slave node and master body (stick condition). The second is when there is relative sliding between contacting bodies (sliding condition).

In order to satisfy the contact conditions, we construct a penalty functional including both terms of contact [44,45]

$$P\equiv\int_{\Gamma_C}\alpha_n\frac{g_n^2}{2}\mathrm{d}\Gamma+\int_{\Gamma_C}\alpha_t\frac{g_t^2}{2}\mathrm{d}\Gamma \tag{5}$$

where α_n and α_t are penalty parameters. Differentiating with respect to $\mathbf{u}$ gives

$$\delta P\equiv\int_{\Gamma_C}\delta g_n(\mathbf{u})^T\alpha_n g_n(\mathbf{u})\mathrm{d}\Gamma+\int_{\Gamma_C}\delta g_t(\mathbf{u})^T\alpha_t g_t(\mathbf{u})\mathrm{d}\Gamma=0 \tag{6}$$

Using penalty method in imposing constraints has several advantages. The number of unknowns does not increase. The system equations maintain the positive definite property. However, the accuracy of the constraint imposition relies on the choice of a suitable penalty parameter. Theoretically, higher penalty number improves the accuracy, however, in practice, choosing very large penalty parameter could cause ill-conditioning of the system equations.

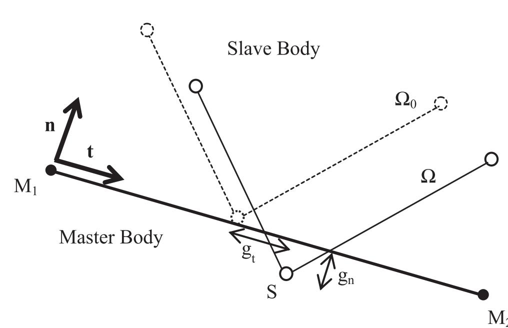

Fig. 1. Basic terminology for contact problem.