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Development and validation of a meshless 3D material point method for simulating the micro-milling process

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ABSTRACT

A meshless generalized interpolation material point method for simulating the micro-milling process was developed. This method has several advantages over well-established approaches (such as finite elements) when it comes to large plastic strains and deformations, since it inherently does not suffer from tensile instability problems. The feasibility of the developed material point model for simulating micro-milling is verified against finite element simulations and experimental data. The model is able to successfully predict experimentally measured cutting forces and determine chip temperatures in agreement with conventional finite element simulations. After having verified the approach, the model was applied to perform extensive numerical 3D simulations of the micro-milling process. The goal is to evaluate the response of the micro-milling cutting forces as function of the hardening behavior of the micro-milled material. The meshless 3D simulations reveal a dependency of tool force slopes (with respect to the uncut chip thickness) on the hardening parameters. Based on these findings, a new approach is outlined to determine hardening parameters directly from two micro-milling experiments with distinct, sufficiently large uncut chip thicknesses.

1. Introduction

The current trend in miniaturizing components requires the development and improvement of suitable machining technologies that are able to perform accurately at the micrometer scale. In this context, micro-milling has emerged as one of the most cost-efficient techniques for manufacturing components with complex micro-features. The success of micro-milling is based on its high performance and versatility, since it can be applied to machining for a great variety of materials. Micro-milling is becoming increasingly relevant due to the high demand in aerospace, automotive, medical, optical, and microelectronics industries for miniaturized systems with superior surfaces and high aspect ratios.

A profound understanding of the micro-milling process is essential for ensuring the reliability of the process. The prediction of the cutting forces during micro-milling is of special interest, since they constitute useful parameters for estimating the design requirements for the tool and equipment. Several empirical and analytical cutting force models were reviewed by Germain et al. (2013). The authors reported that in general, empirical models provide a link between the micro-milling parameters and the cutting forces, so that the hardening behavior of the material is implicitly considered via model parameters that need to be fitted. Conversely, analytical models take into account a larger number of process parameters and include material behavior, but are often handicapped by the simplifications required to obtain a analytical expressions.

A significant amount of fundamental knowledge on milling in general and micro-milling in particular has been obtained using computer simulations. They provide a fast and cost-efficient tool for performing parameter studies in order to optimize process conditions. In the early 2000s, Özel and Altan (2000) utilize the finite element method for simulating high-speed flat end milling. The results of this work showed a qualitative agreement between the simulations and experimental data in terms of predicted forces and location of highest tool temperatures and stresses. The feasibility of applying a 2D finite element model for simulating the micro-milling process of aluminum and steel was shown for the first time by Dhanorker and Özel (2008). Their results revealed a reasonable accuracy in the prediction of temperature distributions and cutting forces. Micro-milling simulations of titanium alloys were performed by Thepsonthi and Özel (2013) with emphasis on the impact of

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cBN coating on tool wear. Their results showed a detailed study of the cutting temperature and forces combined with tool wear. However, despite the detailed analyses of the micro-milling process, the use of a 2D simulation model led to simplifications, since the complexity of a oblique 3D cutting process can not be captured. The extension into a full 3D model was subsequently performed by the authors Thepsonthi and Özel (2015). The 3D model allowed the prediction of 3D chip formation with its related cutting forces, temperatures and wear distributions. These results could be exploited to investigate the impact of milling strategy and tool wear. In summary, the available literature shows that the major advantage of finite element simulations is that they allow the determination of variables that are not readily accessible to experiments, such as chip temperatures, strains, and strain rates. Contrary to empirical and analytical cutting force models, computer simulations are capable of coping with most of the process complexity while simultaneously using advanced material models.

The most widespread simulation tool for investigating micro-milling processes is the finite element method (FEM). In combination with visco-plastic constitutive material models, such as the one by Johnson and Cook (1985), this approach has been extensively used with the increasing availability of commercial FEM codes and computational power. However, as an alternative to both FEM and conventional meshless particle methods, a different approach is taken here, combining grid and particle behavior, the so-called material point method (MPM). The reason is that these established discretization methods come with specific disadvantages. Classic FEM is inappropriate for the large deformations experienced here. While re-meshing is possible, this often leads to excessively small time step sizes and thus large computational overhead, as shown by Torigaki and Kikuchi (1992). CFD-like Eulerian simulations are difficult to perform for solid body behavior and suffer from high numerical diffusion as material is advected on the grid. Lagrangian meshless methods such as smooth particle hydrodynamics (SPH) appear as a worthwhile alternative for treating large deformations as shown by Hoover (2006). SPH was originally developed by Gingold and Monaghan (1977) to simulate the formation of stars in the context of astrophysics. However, these methods are not free from problems either. Traditional SPH with Eulerian kernels suffers from tensile instabilities, where tensile stress states lead to unphysical disintegration of solids, as shown by Swegle et al. (1994) and Mamalis and Vortselas (2012) in the context of micro-scratching. The prevention of tensile instabilities requires large amounts of artificial viscosity and strong *ad-hoc* correction mechanisms, which severely influence the accuracy of the results. The Total-Lagrangian SPH of Ganzenmüller (2015) is a much more accurate reformulation of SPH which utilizes a constant reference configuration to perform the weak-form integration of stresses and strains. While this markedly improves accuracy and eliminates the dreaded tensile instability, the concept of a constant reference configuration is not compatible with truly large deformations, in particular plastic flow, where parts of the material are disconnected and reconnected to different parts upon solidification. Updates of the reference configuration may be performed as shown in Leroch et al. (2016), who used this approach for performing scratch simulations on copper. Recently, Varga et al. (2017) applied the same methodology for simulating scratch tests on austenitic steel, reaching a good agreement in terms of scratch morphology. The method was also applied by Varga et al. (2017a) for performing extensive simulation of scratch tests with the aim of linking the material parameters with the scratch morphology and scratch hardness. However, the main disadvantage of this approach is that it incurs in computational overhead and does not appeal as an elegant solution.

In this work, a particular MPM called the generalized interpolation material point method (GIMP) is applied for the following reasons: it does not suffer from the tensile instability problem, can handle very large deformations, and has been shown to exhibit first-order convergence upon resolution refinement, as shown by Wallstedt and Guilkey (2008). With all these features, as will be shown in the following, GIMP presents itself as a promising method for studying machining problems featuring violent deformations. Introduced in the 1990s by Sulsky et al. (1994), MPM was subsequently further developed and refined by a number of authors, in particular Bardenhagen and Kober (2004), who introduced a Petrov-Galerkin discretization scheme, and Wallstedt and Guilkey (2007), who improved the projection operation for linear functions. Common to all flavors of MPM is the use of Lagrangian particles as in SPH, which contain all the information about the system, e.g., stress, strain, momentum, and histories of these quantities. Additionally, and in contrast to classical particle methods such as SPH, an auxiliary background grid is used to compute strain rates and stresses. Information between particles and grid is exchanged via the use of smooth interpolates, which can be related to the SPH kernel or FEM shape functions. MPM is classified as a true particle method, because the entire grid only serves as a computational scratchpad and is discarded at the end of each time step. The state of the system is then advanced by moving the particles only.

The accuracy of computer simulations depends on the robustness of the hardening models used for predicting the cutting forces and chip temperatures, among others. These models usually rely on parameters that need to be determined via fitting to reference experiments. In the particular case of micro-milling, the use of visco-plastic constitutive models with strain rate and temperature dependence means that the identification of the material parameters requires complex and demanding dynamic stress–strain experiments, such as the Hopkinson bar. As illustrative example of this effort, Hokka et al. (2012) used high temperature and high strain rate compression tests performed on the titanium alloy Ti-15-3 for determining the material parameters of a modified Johnson–Cook model. The results obtained were used to simulate orthogonal cutting, reaching a very good agreement between the predicted and the measured cutting stresses. Consequently, the direct identification of the material parameters from data acquired during the milling process itself would be of paramount technological and scientific relevance. Several attempts to this end have been made in the past by some authors. Shrot and Bäker (2012) applied FEM simulations for inverse identification of the material parameters during milling. The results reveal the ambiguity encountered in the inverse identification of the Johnson–Cook material parameters for steel. In their case, sets of different parameters where found that led to indistinguishable cutting forces and chips. In a follow-up work, Bäker (2015) proposed a method that successfully removed this duality, but still relied on quantities that are not directly measurable in experiments. Therefore, a more profound understanding of the role of the material parameters in the milling process is required for achieving this ambitious goal. The prediction of cutting forces during micro-milling has also been a subject of recent interest by Afazov et al. (2010). Using a semi-empirical equation, the authors correlated the cutting force with the uncut chip thickness and the cutting velocity. The results were verified experimentally using AISI 4340 steel. Later, Afazov et al. (2012) also successfully validated the model using AISI H13 steel with a hardness ranging from 35 and 60 HRC. The influence of tool wear was subsequently taken into account in Afazov et al. (2013). Denkena et al. (2015) developed an inverse determination methodology based on Oxley's machining theory to predict cutting forces for complex three-dimensional tools. When combined with tensile test data, material parameters could be determined using this method. The methodology led to the formulation of a mathematical model for determining the uncut chip thickness.

The aim of the present work is to implement a material point method on the molecular dynamics program LAMMPS developed by Plimpton (1995) and apply the implementation to 3D micro-milling. To our best knowledge, no MPM implementation has been used so far to simulate micro-milling. The model is benchmarked against standard and well-established finite element simulations, and the predicted cutting forces are additionally compared to experimentally measured values. The main advantage of the proposed model is that it is naturally able to handle very large deformations and material detachment, in