Journal of Materials Processing Tech. 256 (2018) 98–108

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

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

FE temperature- and residual stress prediction in milling inserts and correlation with experimentally observed damage mechanisms

Andreas W. Nemetz[a,*], Werner Daves[a], Thomas Klünsner[a], Werner Ecker[a], Tamara Teppernegg[b], Christoph Czettl[b], Ivan Krajinović[a,c]

[a] *Materials Center Leoben Forschung GmbH, Roseggerstraße 12, 8700 Leoben, Austria*
[b] *CERATIZIT Austria GmbH, 6600 Reutte, Austria*
[c] *EPCOS OHG, Siemensstrasse 43, 8530 Deutschlandsberg, Austria*

ARTICLE INFO

Keywords:
Finite element model
Arbitrary Lagrangian-Eulerian (ALE) model
Milling tools
Residual stress
Metal cutting
Comb crack

ABSTRACT

In milling applications thermal and mechanical loadings are affecting the damage behavior of milling inserts. There are several open questions regarding the influence of loading and tool temperature on inelastic deformations and damage mechanisms. The aim of the current work is to simulate industrial milling processes with the finite element method and generate knowledge about the acting damage mechanisms. The validation of the results is made by two recently reported experimental milling setups. The focus of the simulations is set on investigations of the evolution of tensile residual stresses orientated parallel to the cutting edge of a milling insert. These tensile residual stresses foster the formation and growth of so-called comb cracks growing in planes perpendicular to the cutting edge which are detrimental to the performance of the tool. The insert is made of WC-Co hard metal with 8 wt.% Co-binder and an average WC grain size of 1 µm. It is coated with a 7 µm thick TiAlN layer acting as a thermal shield. The workpiece material is 42CrMo4, described by a Johnson-Cook constitutive material model. The milling process is modeled with a 2D Arbitrary Lagrangian-Eulerian (ALE) approach. Results of the 2D simulations are used to generate the temperature and contact load imposed on a 3D solid-model of the milling insert that is in turn used to predict the evolution of stress and temperature over 50 milling cycles. The simulations reproduce a shift of residual stresses toward tension in the milling insert at the same location as observed in experiments from which one failed due to comb cracks and one due to wear.

1. Introduction

The process of metal cutting was numerically modeled by different strategies during the last decades. Most of the developed 2D models reproduce the orthogonal-cutting process using a constant uncut chip thickness in order to gain knowledge of the physics of the process. Orthogonal cutting processes are characterized by a perpendicular arrangement of the cutting edge relative to the feed direction. An introductory literature review describes the framework this paper is based in, places it in context to existing work and motivates the necessary further modeling steps: Ceretti et al. (1996) developed a 2D model using a remeshing technique and a damage criterion to predict chip separation. A variation of the cutting parameters cutting speed, cutting depth and tool rake angle is investigated and the results are validated with experiments. Kone et al. (2011) also used remeshing techniques in their developed 2D cutting models and three tool coating configurations and their influence on the temperature flow into the tool is discussed. Eck et al. (2015) performed a sensitivity analysis in order to investigate the effect of the mesh size, the material model and the friction model on the calculated tool-chip contact length. According to their findings, a Coulomb friction coefficient of 0.4 leads to a realistic simulation of the cutting process. An alternative simulation technique is the Arbitrary Lagrangian-Eulerian (ALE) approach, presented with its theoretical details by Gadala (2004). Nasr et al. (2007) used the ALE technique to design a 2D model able to simulate orthogonal cutting of stainless steel. The induced residual stresses in a near surface layer of the workpiece are investigated. Miguélez et al. (2009) also modeled the orthogonal cutting process using an advanced ALE method including a combination of Lagrangian and Eulerian boundaries with the effect to gain better quality of the mesh during simulation. More recently, advanced models were developed which model a transient cutting condition with non-constant uncut chip thickness: Krajinović et al. (2016) developed an ALE model of the climb milling process and Avevor et al. (2017) presented an ALE model of the conventional milling process. In

---

* Corresponding author.
E-mail addresses: andreas.nemetz@mcl.at (A.W. Nemetz), werner.daves@mcl.at (W. Daves), thomas.kluensner@mcl.at (T. Klünsner), werner.ecker@mcl.at (W. Ecker), tamara.teppernegg@ceratizit.com (T. Teppernegg), christoph.czettl@ceratizit.com (C. Czettl), ivan.krajinovic@epcos.com (I. Krajinović).

https://doi.org/10.1016/j.jmatprotec.2018.01.039
Received 3 November 2017; Received in revised form 23 January 2018; Accepted 26 January 2018
0924-0136/

the work of Klocke et al. (2017), the influence of lubrication on chip formation is investigated numerically, which provides a possible extension for future approaches. A proper numerical model of the metal cutting process includes many different models, such as a friction model, material models and heat transfer models, respectively. Most of the cutting models reported in literature are focused on the numerical prediction of forces, stresses and temperatures occurring during the process. Models developed by Yen et al. (2004) furthermore deal with tool wear by implementing a wear rate model into the FE code.

Damage mechanisms, affecting the service life of milling inserts, are nearly always a combination of some basic phenomena, such as abrasive and adhesive wear, crater wear, dissolution of the cutting edge and cracks, especially comb cracks. The milling process is characterized by interrupted cutting, leading to thermal and mechanical cycling and that supports the formation of comb cracks, as described by Da Silva et al. (2011). The consequences of cyclic thermal loading that induces cyclic mechanical stresses and strains on the accumulated damage near loaded surfaces are investigated by Ebner et al. (2008): Thermal conductivity plays an important role regarding the thermal fatigue resistance of metal cutting tools. Experimental investigations with coated inserts and their influence on the tool-chip interface temperature were carried out by Grzesik (1999): It is shown that a proper selection of the coating enables to control the heat transfer into the substrate of the tool. The exact formation mechanism of comb cracks is not completely understood. Indications are that the expansions and contractions induced by interrupted cutting – as investigated in the work of Nordin et al. (2000) – and localized plastic deformation of the substrate – measured by Teppernegg et al. (2014) – on the milling insert‘s rake face during the milling process play a decisive role in the emergence of comb cracks.

2D models are not suitable to assess the evolution of stresses on the insert`s rake face in a direction orientated parallel to a cutting edge. The fundamental reason for developing 3D models is that stresses orientated in the out-of-plane direction of 2D models are main drivers for the formation of comb cracks. Furthermore, 2D approaches can only model an orthogonal cutting arrangement. Processes in which the cutting edge is not perpendicular to the feed direction – so-called oblique cutting processes – require a 3D modeling.

Some work in the field of 3D modeling of orthogonal cutting and oblique cutting has been done by Ceretti et al. (2000): A model with thermo-elastic-plastic-coupling was developed, simulating the turning process from an incipient state to a steady state of chip formation. Although the tool was modeled as a rigid body, thermal properties are included. A 3D ALE model of oblique cutting was introduced by Pantalé et al. (2004) and the unsteady-state process of chip formation is investigated numerically. Fang and Zeng (2005) presented a 3D model of a turning process with oblique cutting conditions and investigated the influence of the inclination angle of the tool on the force components. Arrazola and Özel (2008) developed a hybrid ALE-remeshing model of an oblique turning process including a tool, modeled with elastic material parameters. This simulation reaches a steady state of the chip´s shape and the temperature fields in the tool and the workpiece are presented. Ducobu et al. (2017) developed a 3D model of orthogonal cutting, using a Coupled Eulerian-Lagrangian approach. The tool is modeled with linear elastic material behavior and the simulation of the lateral expansion of the workpiece material is explored, depending on its lateral mesh size. A 3D transient thermal model of a cutting tool, using a predefined heat flux to calculate the evolution of temperature within the tool was developed by Putz et al. (2017). A 3D model has been applied by Binder et al. (2015), using a methodology of node displacement to simulate tool wear.

The previous cited models simulate either only a period of an initial cycle of milling or the start of the cutting process and heating up of the tool is neglected. This paper fills this gap by introducing a new modeling concept for the prediction of residual stresses and temperature fields in cutting tools developing during several cycles of milling. 3D milling models are currently not able to describe the produced temperature and stress field accurately. Therefore, a comprehensive finite element (FE) modeling concept of a milling process has been developed. The used material parameters of a hard coated hard metal milling insert have been determined experimentally. Results of the 2D milling simulations were used as input for 3D models, which simulate the temperature and stress development in the milling insert during 50 cutting cycles. The simulations of two milling processes predict residual stress fields that are observed and correlate in position with comb cracks formed in real milling inserts. The experiments were performed from our group and are already reported in Teppernegg et al. (2014).

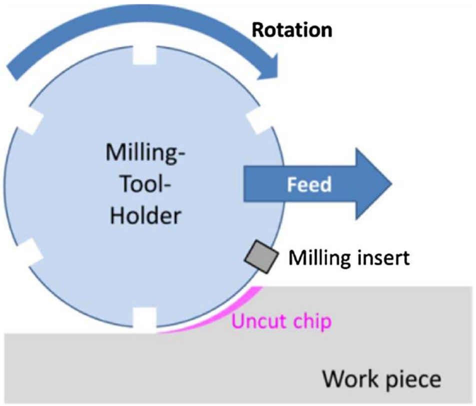

Fig. 1. Scheme of the investigated climb milling process.

2. Numerical modeling of milling processes

This section provides an overview of the developed finite element models, used to simulate climb milling processes, as represented in Fig. 1. A single TiAlN coated milling insert is clamped on a milling tool holder, which rotates with a speed of 560 rpm and additionally moves forward with a feed rate $f_z = 0.4$ mm/rotation and $f_z = 0.5$ mm/rotation, respectively. The diameter of the milling tool holder is 125 mm and the cutting speed is 220 m/min. As in the experimental process, there is no cooling agent involved, such as lubricant or pressurized cool air. The applied depth of cut is $a_p = 4$ mm. The milling insert cuts workpiece material during a time period of 14 ms and needs additional 92 ms to finish the entire tool holder revolution and reach the initial position again. Throughout one rotation, the milling insert is heating up during the cutting process and is cooling down during the following idle period. To simulate the entire milling process – consisting of alternating heating up and cooling down phases – several steps are necessary, as indicated in Fig. 2. Basis of the approach is a coupled thermo-mechanical 2D plane strain model of the cutting process, which on the one hand supplies time dependent temperatures on the surface of the milling insert and on the other hand provides 2D contact forces, generated during contact between tool and workpiece. The surface temperatures are used as boundaries at the surface of a developed thermal 3D model of the milling insert, enabling to calculate the transient 3D temperature field within the milling insert over multiple milling cycles. The calculated 3D temperature field is then used as a predefined field in the final 3D model of the milling insert and the mechanical load originated from the 2D model is applied on it. The scheme of the stepwise modeling approach is outlined in Fig. 2.

2.1. 2D FE-milling model

The coupled thermo-mechanical 2D model of the milling process (Fig. 3) – a plane strain model – consists of the workpiece material and the coated milling insert. The insert follows a circular path to simulate the rotation of the milling tool holder with the mounted milling insert while the workpiece material is fixed in space. This is a simplification of