C. R. Mecanique ••• (••••) •••–•••

Contents lists available at ScienceDirect

Comptes Rendus Mecanique

www.sciencedirect.com

Computational modeling of material forming processes / Simulation numérique des procédés de mise en forme

3D numerical simulation of drilling residual stresses

Mathieu Girinon [a], Frédéric Valiorgue [b], Habib Karaouni [c], Éric Feulvarch [b,*]

[a] *CETIM, 52, avenue Félix-Louat, 60300 Senlis, France*
[b] *Univ. Lyon, ENISE, LTDS, UMR 5513 CNRS, 58, rue Jean-Parot, 42023 Saint-Étienne cedex 2, France*
[c] *SAFRAN Tech, rue des Jeunes-Bois, 78772 Magny-les-Hameaux, France*

ARTICLE INFO

Article history:
Received 27 October 2017
Accepted 21 December 2017
Available online xxxx

Keywords:
Drilling processes
Residual stresses
Numerical simulation

ABSTRACT

Drilling can affect the integrity of the surface of a mechanical component and reduce its fatigue life. Thus, drilling parameters such as lubrication or drilling velocity must be optimized to ensure a satisfactory residual mechanical state of the hole surfaces. Unfortunately, experimental tests are time consuming and it is not easy to observe the cutting process because of the confinement of the drill zone. The literature does not exhibit any numerical simulation capable of simulating 3D thermomechanical phenomena in the drill zone for large depth holes. Therefore, residual stresses cannot be easily simulated by means of the sole drilling parameters. The aim of this article is to propose a new numerical approach to compute drilling residual stresses for large-depth holes. A first simulation is developed to simulate heat transfer by means of a 3D thermoviscoplastic simulation in a new Rigid-ALE framework allowing the use of large calculation time steps. Then, a time interpolation and a spatial projection are implemented to rebuild the Lagrangian thermal history of the machined component. Finally, a thermo-elastoplastic simulation is carried out to compute residual stresses in the final workpiece. In this paper, the method is applied to a 316L austenitic stainless steel in the case of an unlubricated hole. The computed residual stresses are compared to experimental measurements.

1. Introduction

During the manufacturing of aeronautical, nuclear or medical parts, drilling processes are often used to perform holes. All the machining processes impose thermal and mechanical loadings on the machined part, which modifies the surface integrity and thus, the fatigue lifetime. Compared to other processes such as turning or milling, the experimental study of drilling is difficult because of the confinement of the drill zone. To avoid such an issue, numerical simulation is of particular interest, since it allows studying the local thermomechanical phenomena in 3D.

Different types of numerical models are developed in the literature for drilling processes. The less predictive models use temperature measurements to estimate thermal loadings, as proposed by Huang et al. [1] and Sousa et al. [2]. These models do not consider the mechanical coupling in the heat generation process, but they can provide thermal input data to study phase transformations as proposed by Schulze et al. [3]. Wu and Han [4] developed a numerical model in 2D by means of various finite element codes. They studied the cutting area near the center of the drill zone and in the main cutting

---

[*] Corresponding author.
E-mail address: eric.feulvarch@enise.fr (É. Feulvarch).

https://doi.org/10.1016/j.crme.2018.06.003

Please cite this article in press as: M. Girinon et al., 3D numerical simulation of drilling residual stresses, C. R. Mecanique (2018), https://doi.org/10.1016/j.crme.2018.06.003

zone in planes perpendicular to the cutting edge to determine where the temperature is highest. Ozcelik and Bagci [5] also used a 2D numerical approach to study the cutting phenomena along the cutting zone, and they compared results for two materials: AISI 1040 and Al 7075-T651. This 2D approach is unable to give the 3D thermomechanical loadings required for studying the surface integrity of the final holes.

Most of the existing 3D numerical models in drilling processes pose challenges to simulate the machining of a significant drilling depth. Nan et al. [6] simulate a drilling time of about 0.03 s by means of Abaqus/Explicit. Abouridouane et al. performed several studies on the thrust force, the torque and the chip geometry for micro-drilling with Deform-3D [7][8][9]. They also studied a classical drilling configuration with a drill diameter of 8 mm [10] and the simulated time was about 80 ms, which corresponds to a small depth. A similar configuration was studied by Marusich et al. [11] with the code Third Wave Advantedge, whereas Muhamad et al. used MSC Marc [12] and Deform-3D [13]. To simulate the removal of the material, these numerical models are based on an explicit time integration leading to a very high computation time. Moreover, they use a Lagrangian description for the material movement description. Therefore, the computing time is increased because of the need for successive remeshing operations to avoid mesh distortions. Thus, the drilling time simulated is always low and only thrust force, torque and chip geometry can be compared with the experimental data.

The literature does not exhibit any numerical simulation capable of simulating 3D thermomechanical phenomena in the drill zone for very deep holes. In turning processes, Valiorgue et al. [14] avoid the simulation difficulties of the chip generation by replacing the physical effects of the cutting zone by an equivalent thermomechanical loading applied on the final surface after machining. This loading is built intuitively from experimental measurements. To avoid such an intuitive stage, a new numerical approach is proposed in section 2 of this paper to compute drilling residual stresses for holes of large depths. In section 3, a first simulation is developed to simulate heat transfer by means of a 3D thermoviscoplastic simulation in a new Rigid-ALE framework. In section 4, a time interpolation and a spatial projection are implemented to rebuild the Lagrangian thermal history of the machined component. Thus, a thermo-elastoplastic simulation can be carried out to compute residual stresses on the final geometry. The whole method is applied to an 316L austenitic stainless steel in the case of an unlubricated hole. The computed residual stresses are compared to experimental measurements.

2. A new numerical strategy

From the computational point of view, the main difficulty lies in the simulation of chip generation. Indeed, this needs the use of a damage model, difficult to calibrate because of the material's elasticity, which prevents the separation of the chips from the rest of the material. Moreover, elasticity imposes to track the material flow and this can lead to mesh distortions requiring remeshing steps and projections of results from one mesh to another. In 3D, such an approach is very CPU time consuming. Unfortunately, the computation of drilling residual stresses needs to take account of the elasticity. In this work, we propose to compute residual stresses by means of a step-by-step method that is composed of two successive simulations, as shown in Fig. 1.

The objective of the first one is to simulate the thermomechanical effects due to the removal of the material by means of the drilling process parameters. This thermomechanical simulation is based on a viscoplastic behavior law avoiding elasticity and, therefore, on the use of a damage model. As far as the mesh is concerned, a new Rigid-ALE technique is proposed to avoid mesh distortion. The method R–ALE combines the Lagrangian, Eulerian, and ALE characteristics according to the part of the model considered. A part of the mesh can move between two successive configurations without distortions by means of rigid movements. Because we do not consider elasticity, hardening, and damage, there is no need to project the results from one mesh to another. The material time derivatives are classically treated by means of the standard ALE technique, which consists in defining a convection velocity relatively to the mesh movement. To reduce the computing time, a backward Euler algorithm tolerating relatively large time steps is adopted for time integration. After the R–ALE simulation, a transfer step is carried out for rebuilding the Lagrangian history of the final workpiece in terms of temperatures in the case of an unlubrificated drill. Thus, a Lagrangian thermo-elastoplastic computation can easily be carried out for computing residual stresses.

3. Thermo-mechanical R–ALE simulation of the drilling process

3.1. Physical modeling

3.1.1. Material flow

Assuming that viscous stresses are predominant, the momentum balance is governed by the following equation:

$$\mathbf{div}(\boldsymbol{\sigma}) = \mathbf{0} \tag{1}$$

$\boldsymbol{\sigma}$ denotes the Cauchy stress tensor:

$$\boldsymbol{\sigma} = \mathbf{S} - \mathrm{p} \cdot \mathbf{I}$$

where p is the hydrostatic pressure, **I** is the unit second-order tensor and **S** is the deviatoric stress tensor. As for hot forming processes, a viscous behavior law is used to model the material flow in the cutting area. This law can be represented as follows:

Please cite this article in press as: M. Girinon et al., 3D numerical simulation of drilling residual stresses, C. R. Mecanique (2018), https://doi.org/10.1016/j.crme.2018.06.003