International Journal of Machine Tools & Manufacture 68 (2013) 63–74

Contents lists available at SciVerse ScienceDirect

International Journal of Machine Tools & Manufacture

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

Stability of lateral, torsional and axial vibrations in drilling

K. Ahmadi, Y. Altintas *

Manufacturing Automation Laboratory, Department of Mechanical Engineering, The University of British Columbia, Vancouver, BC., Canada V6T 1Z4

ARTICLE INFO

Article history:
Received 20 September 2012
Received in revised form
13 January 2013
Accepted 15 January 2013
Available online 8 February 2013

Keywords:
Chatter
Whirling
Drilling
Process damping

ABSTRACT

Instability caused by whirling, lateral and torsional-axial modes of the drill causes dimensional inaccuracies of the holes and may damage the drills. A generalized stability model for drilling dynamics is presented in this paper. The model considers the regeneration of chip thickness due to the tool deflection in the lateral, torsional and axial directions. The tool wear is considered on damping of high frequency, torsional vibrations during drilling process. The stability for whirling, lateral and torsional axial chatter is predicted simultaneously and analytically in semi-discrete time domain. The stability model is experimentally verified by conducing series of drilling tests with a sharp and worn tool.

1. Introduction

The dimensional accuracy, roundness and surface quality of the holes are greatly influenced by the vibration of the drill bit. Three modes of vibration occur in drilling operations: lateral chatter, torsional-axial chatter and whirling. One or more of these vibration modes may grow unstable at a time. While chatter develops at the frequencies close to the natural modes of the drill, whirling develops at the multiples of spindle frequency. Whirling instability results in multisided holes; lateral and torsional-axial chatter result in violating the dimensional tolerances and damage to the tool. Predicting the "stable" cutting parameters is essential for avoiding costly trials, reworks and post-drilling operations.

In machining processes, the vibration instability due to the feedback between subsequent cuts is regarded as self-excited or regenerative chatter [1]. Modeling this phenomenon in various machining operations has been the subject of vast amount of studies in the literature [2]. The fundamentals of regenerative chatter in drilling were developed by Tobias and Fishwick in [3]. They formulated the chip regeneration in drilling and developed the stability lobe diagrams. Galloway studied the effect of cutting tool geometry on the roundness and dimensional accuracy of the hole [4]. Ema et al. developed a model for the lateral chatter of drilling [5]. They also studied the effect of various factors on the stability of the cut and used impact dampers to suppress the lateral chatter of the drill [6]. Huang in [7] simulated the dynamics of micro-drills with the beam theory and investigated the varying boundary condition when the tool drills into a deep hole. Tekinalp and Ulsoy in [8] used Finite Element Modeling to study the dynamics of drill bits under different geometries, rotational speeds and boundary conditions. Rincon and Ulsoy studied the effect of gyroscopic effect and coriolis forces on the dynamics of drill bits in [9]. However, the effect of regeneration was not considered in their work. Bayly et al. developed a single degree of freedom model to study the torsional-axial chatter in drilling [10]. In their study, torsional-axial stability lobes were developed and verified experimentally. They simulated the drill bit with a pre-twisted beam in the torsional-axial mode; by applying torque, the beam unwinds and results in chip regeneration. Arvajeh and Ismail in [11] presented the lateral chatter stability lobes; they studied the effect of gyroscopic and coriolis forces on the stability diagrams. In [12], Arvajeh and Ismail conducted a time domain simulation for the combined torsional-axial and lateral chatter. Roukema and Altintas conducted a comprehensive time domain simulation of the drilling process in [13]. Their model included the nonlinearities, different drill geometries, and all of the vibration modes. They also presented a combined lateral and torsional-axial chatter model, and used a frequency domain solution to establish the generalized stability lobes, both in the lateral and torsional-axial modes [14]. While their stability diagrams agreed very well with the ones obtained from other methods in the literature such as [10,11] they underestimated the stability borders. The source of this underestimation is attributed to the un-modeled process damping effect.

The formation of multisided holes due to the whirling motion of drills has been studied in several articles such as [15]. Ema

* Corresponding author. Tel.: +1 604 822 5622; fax: +1 604 822 2403.
E-mail address: altintas@mech.ubc.ca (Y. Altintas).
URL: http://www.mal.mech.ubc.ca (Y. Altintas).

0890-6955/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijmachtools.2013.01.006

et al. in [16–18] conducted a set of experiments and showed that the whirling vibration of the tool grows unstable when the cutting edges start "rubbing" against the machined surface. The vibration of the drill bit generates waviness on the machined surface, which becomes extruded under the flank face of the tool. This phenomenon has been studied in several works such as [19,20] for turning and milling, where it is shown to be the major source of process damping and higher stability at low cutting speed [21]; shorter waves generated at low cutting speeds, lead to higher damping. In addition to the higher stability at low cutting speeds, Ema et al. observed whirling instability in the presence of process damping [16]. Bayly et al. in [22] developed a quasi-static model of drilling in which they designated the effect of process damping with a viscous damper. By increasing the damping coefficient, they showed that some of the whirling modes may grow unstable. Their analysis verified experimental observations of Ema et al. reported in [16]. Later, Bayly's group extended their quasi-static model to a full dynamic model, which includes whirling as well as lateral chatter in [23]. Their work confirmed that, process damping leads to a higher chatter stability limit at low cutting speeds, where whirling instability at low frequency arises.

In this paper a new model of drilling dynamics is presented. The lateral, axial and torsional deflections of the drill bit are included in the model. In addition, the effect of process damping is considered by adapting the indentation model of plowing forces. Therefore, the presented model predicts the stability limit due to whirling as well as chatter. The stability limit can be determined regardless of the mode of vibration, or individually for each of the three modes (whirling, lateral and torsional-axial chatter). Semi-Discretization Method (SDM) [24] is used to determine the limit of stable radial depth of cut at each spindle speed. The accuracy of the presented approach in predicting the stability limits is verified by a set of experimental observations.

In the next two sections the dynamic model, cutting forces and process damping model is explained. It is followed by a brief explanation of SDM in Section 4 and the experimental results in Section 5.

2. Dynamic model of drilling

The geometry and dynamic model of a conventional drill is shown in Fig. 1(a). The dynamic model considers four degrees of freedom: the tool's lateral deflection in two orthogonal directions, u and v; its deflection in the axial direction, z; and its torsional deflection around the Z axis, θ. The lateral deflection is assumed to be decoupled from the deflections in the axial and torsional

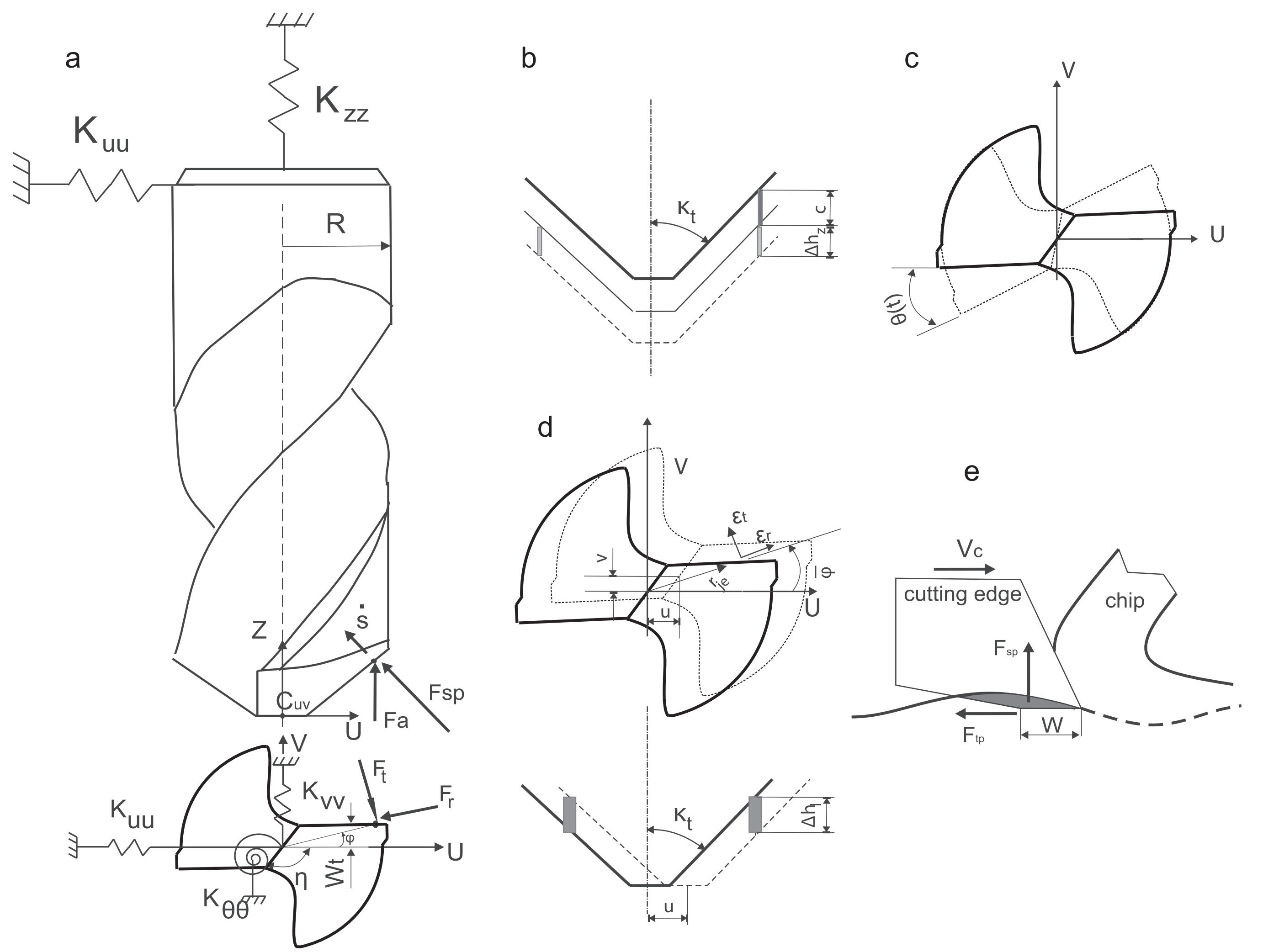

Fig. 1. (a) Geometry of a conventional drill; lateral (u and v), axial (z) and torsional degrees of freedom; tangential (F_t), radial (F_r) and axial (F_a) components of the cutting forces. (b) The static chip thickness (c) contributed by the axial feed and (Δh_z) contributed by the axial deflection of the drill. (c) The torsional deflection of the drill. (d) The lateral deflections of the drill and the chip thickness variation contributed by them (Δh_l). (e) The generation of process damping forces due to the compression of undulation under the flank face of the cutting edges.