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A numerical simulator to predict the dynamical behavior of the self-vibratory drilling head

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Abstract

The manufacturing of deep holes has to face problems to evacuate chips, especially for small diameters. Such problems induce frequent tool breakage and poor surface quality. The vibratory drilling enables the chip to be split into small elements thanks to the axial vibrations of the drill, self-maintained by the cutting energy. Thus, chips are easily evacuated from the hole. A specific tool holder with an adapted axial stiffness has been developed in order to investigate this drilling process. The cutting conditions are predetermined in order to lead to axial vibrations with a stable frequency and amplitude. During a period, the amplitude of the vibrations is higher than the feed per revolution, which enables the cutting edges to jump out of the work material. The vibrations are self-maintained and remain stable if some disturbances are absent or very limited such as the friction of the drill against the work material along its margins, the ploughing force induced by the chisel edge, the ploughing force induced by clearance face, etc. The objectives of this paper are (i) to model the dynamical behavior of the self-vibrating drilling head, the cutting and ploughing forces, and the material removal, (ii) to foresee with a numerical simulator the cutting conditions which generate good vibrations, (iii) to validate the numerical simulator with a experimental round of test. This work has also shown that the productivity of the drilling is improved by the use of the vibratory drilling. Deep hole (ratio deep/drill diameter >20) can be drilled with this new technology without any coolant and any retreat cycle with the same quality as a conventional drilling operation.

Keywords: Drilling; Self-excited vibration; Ploughing; Chatter; Numerical simulation

1. Introduction

The deep hole drilling operation remains an unsatisfactory technology for industry since its productivity is rather limited. The main limit for the increase of productivity is directly related to the poor chip evacuation. One solution consists in the application of internal high pressure lubrication to push chips out of the hole. This solution consumes a lot of energy and necessitates an additional equipment that is very costly. Moreover, the use of lubricant is very detrimental from the environmental point of view. Another solution, so called "retreat cycles", leads to stopping the drilling operation and to remove fast the drill from the cutting area and to return back to the drilling area and so periodically when drill's flutes are full. This second solution is very detrimental to the productivity. New techniques of machining have emerged over the last few years to improve chip evacuation. One of these techniques is based on chip fragmentation due to an axial vibration of the drill. Various solutions have been developed in this area, depending on the technical solutions used to generate the vibrations and depending on the frequency/amplitude targeted. It is possible to distinguish the self-vibratory drilling technology [1] and the vibration-assisted drilling. Among the vibration-assisted drilling technologies, some use low frequency (up to 1 kHz) [2–10] and others use ultrasonic-assisted drilling (from 1 to 40 kHz) [11–15].

Among the vibration-assisted technologies, several technical solutions exist. Gouskov [2] evaluated the amplitude and the frequency of the axial movement of a twist drill to

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Nomenclature

a	feed for one revolution (m)
A_c	chip area (m^2)
A_p	area of ploughing (m^2)
c	damping
d	coefficient
F	thrust force (N)
F_z	axial force created by the material removal in zone 1 (N)
F_c^1, F_c^2, F_c^3	cutting force in zones 1, 2 and 3 (N)
F_p	axial force created by the ploughing (N)
h	instantaneous uncut chip thickness (m)
k	stiffness (N/m)
K_t^1	specific cutting coefficient for zone 1 (N/m^2)
K_t^2	specific cutting coefficient for zone 2 (N/m^2)
K_t^3	specific cutting coefficient for the indentation zone (N/m^2)
K_p	specific cutting coefficient for ploughing (N/m^3)
K_r	coefficient
K_v	coefficient
N	number of sub-division of the cutting edge
N_c	number of cutting lip on the drill
q^1, q^2, q^3	coefficient for the cutting model
R	radius of the drill (m)
R_2	radius of zone 2 (m)
R_3	radius of indentation zone (m)
V	cutting speed in a determined point (m/min)
V_{zmax}	feed speed of the drill (m/min)
$X0, Y0, Z0$	estimation of the axial position, speed and acceleration of the drill
γ	rake angle (degree)
α	clearance angle (degree)
δ	point angle (degree)

split the chip. Suciu [3] proposed a tool holder in which the axial vibrations were generated by variation of an oil film between two trays, one of them being in rotation. Chabra [4] suggested creating these axial vibrations by means of linear engines, which equip more and more machine tools today. Toews [7] uses piezolectric system to induce the axial movement. However, these devices require an external power supply on the tool holder that is animated by the movement of rotation. Such systems are difficult to install on a standard machine tool involved in production among other cutting technologies.

Another approach consists in using the cutting energy in order to create natural axial vibrations necessary to split the chip [1,16]. This technology does not need an external adjunction of energy. The regenerative vibrations naturally appear at certain revolution frequencies. The challenge is to stabilize them at a suitable frequency and magnitude for a good chip fragmentation. Indeed, the axial vibrations at low frequency have an amplitude larger than the feed rate. This enables the interruption of the cutting process, leading to small chips. The centrifugal force, combined with the helical flute, enables to evacuate chips easily without any internal coolant.

This technology requires the development of a self-vibrating drilling head (SVDH). The SVDH (Fig. 1) is based on the natural vibration of a solid (m: drill-holder) combined with a spring (k) submitted to the thrust force of the drill. Vibrations appear for adequate cutting parameters by using the low stiffness of the spring located between the body and the drill-holder. This low rigidity part creates conditions for controlled axial regenerative vibrations. To ensure a good quality of the vibratory drilling, the variation of thrust force must be controlled. Thrust force depends on the geometry of the drill and especially of its chisel edge. The principal limit of this technology is mainly related to the damping of the vibrations (c) due to several parameters such as ploughing effect and friction of drill's margins on the hole.

A numerical simulation of the system makes it possible to predict the vibratory domain of the drilling operation. The global model requires three types of input model: a vibratory model of the SVDH, a thrust force model bringing the energy to the system, and a spatiotemporal model predicting the position of the drill with regard to the hole at any time.

Section 1 will describe the dynamic model of the SVDH.

Concerning the thrust force model, it depends on the tool design (geometry, material), on the work material, on the instantaneous uncut chip thickness and on the cutting speed. Standard thrust force models coming from the literature are not relevant for such an application, since they do not consider the ploughing effect or the extrusion of the work material near to the chisel edge, which are strong damping phenomena. They basically have a macroscopic view of the thrust force. The development of a more comprehensive thrust force model considering these elements is necessary. It is important to keep in mind that, inside the theoretical instable domain, vibrations may not

Fig. 1. The self-vibrating drilling head.