Modeling Thrust Cutting Force and Torque in a Vibratory Drilling Process of Titanium Alloy Ti6Al4V

Nawel Glaa
URMSSDT, Engineering National High School of Tunis (ENSIT), University of Tunis (UT), 5 Avenue Taha Hussein
P.B. 56 Bab Mnara 1008 Tunis, Tunisia
E-mail: glaanawel@hotmail.com

Kamel Mehdi
Preparatory Institute for Engineering Studies El Manar (IPEIEM), University of Tunis EL Manar (UTM),
P.B. 244, 2092 Tunis, Tunisia
E-mail: kamel.mehdi@ipeiem.utm.tn

***Abstract*—The drilling operation is considered by manufacturers as complex and difficult process (rapid wear of the cutting edge as well as problems of chip evacuation). Faced with these failures, manufacturers have shifted in recent years towards the drilling process assisted by forced vibrations. This method consists to add an axial oscillation with a low frequency to the classical feed movement of the drill so as to ensure good fragmentation and better chip evacuation.**

This paper presents a model for prediction of cutting forces and torque during a drilling operation assisted by forced low-frequency vibration of titanium alloy Ti6Al4V. The model allows understanding the interaction between the tool and the workpiece and numerically identifying the thrust cutting force and torque generated by the vibratory drilling operation. The effects of cutting and tool parameters on the thrust cutting force and drilling torque will be discussed.

***Index Terms*—Vibratory drilling, Drilling cutting forces, Regenerative Chatter, Numerical Simulation.**

I. Introduction

Metal cutting is usually accompanied with vibrations between the cutting tool and the workpiece. These vibrations are generated by the periodic variation of the chip section causing displacements between the tool and the workpiece, affecting variations of cutting forces and making the cutting process instable. In the case of turning and milling process, the vibrations have a negative effect on the final surface roughness, the precision of the machining cutting conditions and tool life cycle. However, in the case of drilling process, the axial vibration between the cutting tool and the workpiece can be a solution for easy chip evacuation [1]. In recent years, numerous studies on drilling have developed different experimental approaches and formulated mathematical models in order to simulate drilling process. Chen [2] has proposed a concept of delamination factor F_d (i.e. the ratio of the maximum diameter D_{max} in the damage zone to the hole diameter D) to analyze and compare easily the delamination degree in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates. Experiments were carried out to investigate the variations of cutting forces with or without onset of delamination during the drilling operations. The effects of tool geometry and drilling parameters on cutting force variations in CFRP composite materials drilling were examined. The experimental results show that the delamination-free drilling processes may be obtained by the proper selections of tool geometry and drilling parameters. The effects of drilling parameters and tool wear on delamination factor are also presented and discussed.

Tsao and Hocheng [3] have studied the effect of chisel length and associated pilot hole on delamination when drilling composite materials. They presented an analytical approach to identify the process of chisel edge length relative to drill diameter for delamination-free drilling based on linear elastic fracture mechanics. The predicted critical thrust force agrees fairly with the experimental results. Experimental results indicate that the critical thrust force is reduced with pre-drilled hole, while the drilling thrust is largely reduced by cancelling the chisel edge effect.

Guibert and Paris [4] have presented a numerical model for the study of the influence of the ploughing effect on the vibratory drilling behavior. They showed that drilling tools are composed of two main parts: the cutting edge and the chisel edge. These two parts can be divided into three different zones which work differently during drilling operations: A primary cutting edge, which realized the majority of the chip formation by a material removal phenomenon. A secondary cutting edge, which cut the material and where the cutting angles are mainly negative. And the centre of the chisel edge, which does not cut but only spreads the material sideway by an indentation mechanism.

Manuscript received March 14, 2018; revised May 12, 2019

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doi: 10.18178/ijmerr.8.4.607-612

Zitoune et al. [5-7] have investigated an amount of efforts to understand experimentally the drilling process of CFRP/Al stack with carbide drills (K20). The experimental results show that the quality of holes can be improved by proper selection of cutting parameters. This is substantiated by monitoring thrust force, torque, surface finish, circularity and hole diameter.

Recently, Glaa et al. [8] have presented a numerical model for prediction of cutting forces and torque during a drilling operation including the effect of the regenerative chatter and of the cutting process damping. The corresponding algorithm allows understanding the interaction between the tool and the workpiece and numerically identifying the three-dimensional evolution of the cutting force components and cutting torque generated by the drilling process of a titanium alloy. Verification tests are conducted on a vertical machine for titanium alloy Ti6Al4V and the effectiveness of the model and the algorithm is verified by the good agreement of simulation result with that of cutting tests under different cutting conditions.

In the present paper, we will consider a modified model of [8] during a drilling operation assisted by forced low-frequency vibration in the feed direction of the tool. The modified model allows numerical identification of the three-dimensional evolution of the cutting force components generated by the vibratory drilling process. We will discuss in particular the influence of the vibration behavior of the tool on the machining processes (thrust cutting force and drilling torque).

In a first section, we will present the mechanics of the vibratory drilling process. In a second section, we will present a discussion of the effects of cutting and tool parameters on the thrust cutting force and drilling torque. In this stage of research, we propose to test the model by simulating the drilling process of titanium alloy Ti6Al4V. In a future work we will apply the model on drilling process of CFRP/Al or CFRP/Ti stack and we will compare numerical results to experiment results.

II. Mechanics of the Vibratory Drilling Process

Fig. 1 shows a schematic representation of vibratory model of drilling process. The main difference between this model and the model presented in [8] is the additional forced vibration in the feed direction of the tool. The force created by these vibrations is assumed to be equal to $M_{vib}\ddot{Z}_{vib}(t)$ where $\ddot{Z}_{vib}(t)$ represents the acceleration vibration vector and M_{vib} is the mass of the vibratory system. In this case, the novel vibratory drilling process can be modeled by the following motion equation

$$[M]\ddot{U}(t)+([C]+[C_c])\dot{U}(t)+[K]U(t)=F_s(t)+M_{vib}\ddot{Z}_{vib}(t), \quad (1)$$

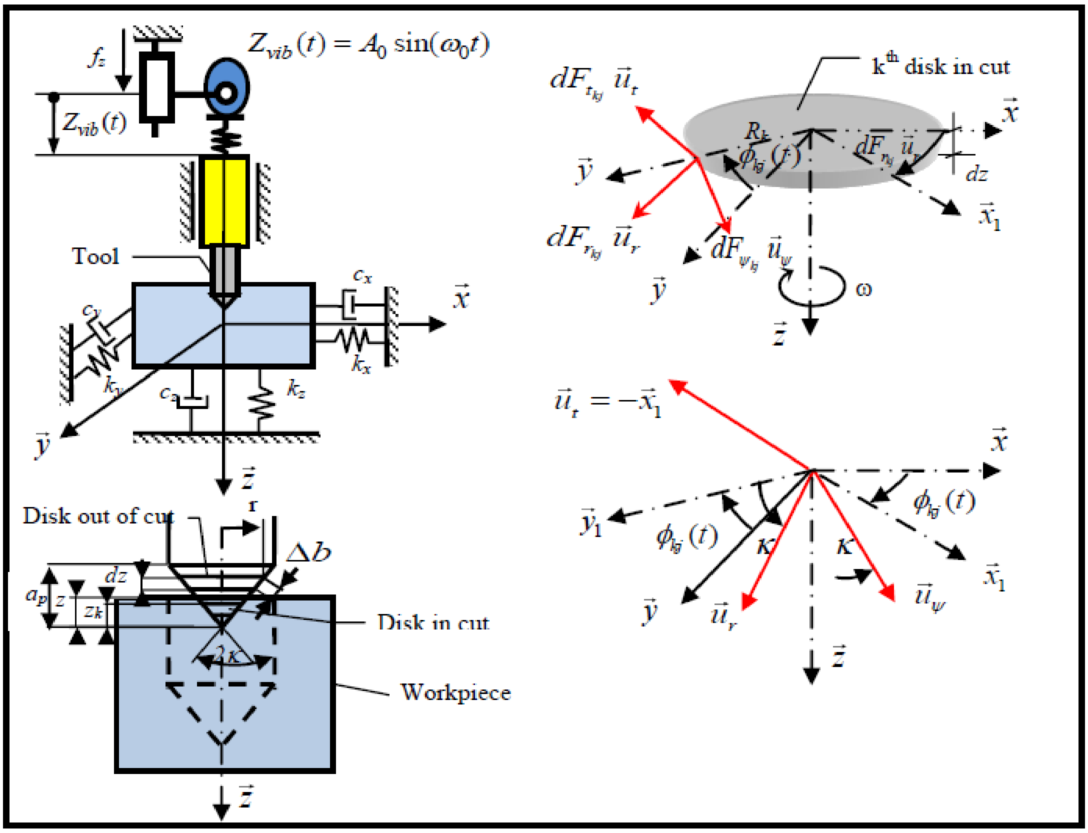

Figure 1. Schematic representation of the kinematic vibratory drilling process

$[M]$, $[K]$ and $[C]$ represent respectively the mass, stiffness and the viscous damping matrices of the workpiece. The tool is discredited into N_d elementary cutting disks of thickness dz.

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Where:

$$[M]=\begin{bmatrix} m_x & 0 & 0 \\ 0 & m_y & 0 \\ 0 & 0 & m_z \end{bmatrix},\ [K]=\begin{bmatrix} k_x & 0 & 0 \\ 0 & k_y & 0 \\ 0 & 0 & k_z \end{bmatrix},$$

$$[C]=\begin{bmatrix} c_x & 0 & 0 \\ 0 & c_y & 0 \\ 0 & 0 & c_z \end{bmatrix},\ U(t)=\begin{pmatrix} u_x(t) \\ u_y(t) \\ u_z(t) \end{pmatrix},$$

$$Z_{vib}(t)=\begin{pmatrix} 0 \\ 0 \\ A_0\sin(\omega_0 t) \end{pmatrix}$$ and

$$[C_c]=\begin{bmatrix} C_{xx}(t) & C_{xy}(t) & C_{xz}(t) \\ C_{yx}(t) & C_{yy}(t) & C_{yz}(t) \\ C_{zx}(t) & C_{zy}(t) & C_{zz}(t) \end{bmatrix}$$

The vector $U(t)$ models the relative displacements between the tool and the workpiece. The vector $Z_{vib}(t)$ is defined in this study by $A_0\sin(\omega_0 t)\vec{z}$ and represents the additional forced vibration system in the feed direction of the tool. A_0 and ω_0 are respectively the amplitude and the period of the forced vibrations.

$F_s(t)$ is the shearing cutting force vector.

$[C_c]$ is the cutting damping matrix used for the calculation of the damping cutting force $F_d(t)$.

$$F_d(t)=[C_c]\begin{Bmatrix} \dot{u}_x(t) \\ \dot{u}_y(t) \\ \dot{u}_z(t) \end{Bmatrix}, \qquad (2)$$

The lecture can find the analytical expressions of $F_s(t)$, $[C_c]$ and $F_d(t)$ in [8].

The sum of the shearing cutting force $F_s(t)$ and the damping cutting forces $F_d(t)$ represents the instantaneous total cutting force vector $F(t)$ acting by the tool on the workpiece.

III. Numerical Simulation: Illustrative Example and Discussion

In this section we will discuss the effect of the additional forced vibration, the cutting parameters (feed rate and tool revolution speed) and the tool parameters (tool diameter and helix angle) on the thrust cutting force and torque.

A. Effect of Additional Forced Vibration

In order to present the effect of additional forced vibration on thrust and drilling torque, two numerical tests have been investigated. The first test (1.0) was without additional forced vibration and the second test (1.1) was with additional forced vibration. These tests have in common the same cutter parameters and the same cutting parameters. Table 1 shows the numerical values utilized in Test 1.1. The amplitude of vibrations in Test 1.0 is considered 0. Fig. 2 shows the effect of the additional forced vibration on the thrust force and the drilling torque. The variation of the thrust cutting force Fz_1.1 and torque Mz_1.1 with the additional forced vibration takes place respectively around the cutting force Fz_1.0 and torque Mz_1.0 without additional vibration. The variation of the thrust cutting force can be a solution for good fragmentation and better chip evacuation. However, the variation of the drilling torque can be the origin of the tool breakage by fatigue phenomenon.

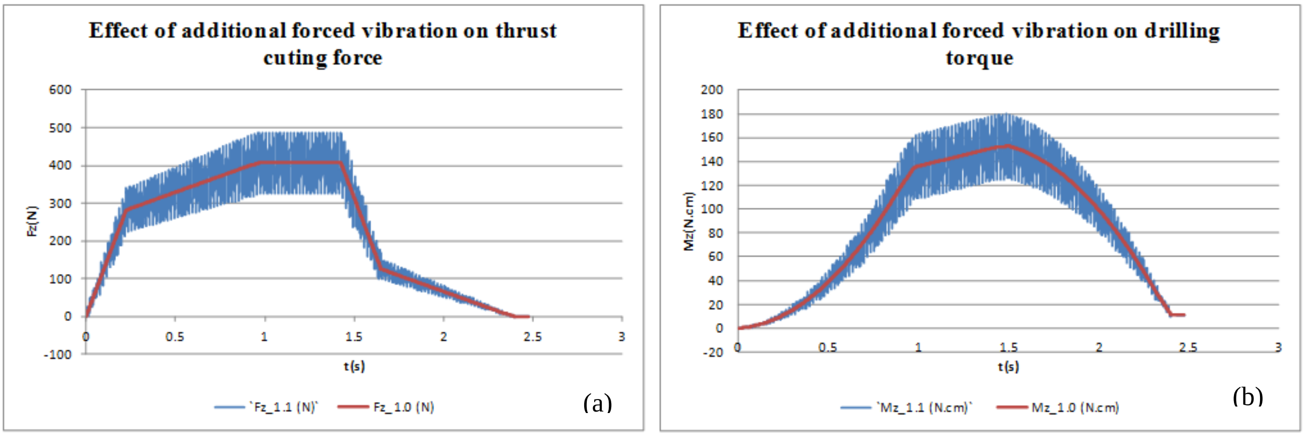

Figure 2. Effect of additionnal forced vibration on thrust cutting force (a) and on drilling torque (b)

B. Effect of Cutting Parameters

In this first test companion, we propose to study the effect of the feed rate and the rotational speed of the tool on the thrust cutting force and the drilling torque. To achieve this objective, data in Table 1 have been considered.

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TABLE I. FIRST TEST CAMPAIGN: EFFECT OF CUTTING PARAMETERS

Cutter geometry parameters (tungsten carbide tool K20)				
Diameter (mm)	6.35			
Helix angle (°)	32.5			
Tip angle (°)	136			
Number of teeth	2			
Radial rake angle (°)	10			
Clearance angle (°)	8.58			
Width of the chisel edge (mm)	0.16			
Additional forced vibrations				
Mass of the vibratory system (g)	25			
Frequency of vibrations (Hz)	50			
Amplitude of vibrations (mm)	0.01			
Cutting parameters for the four tests				
Test Number	**1.1**	**1.2**	**1.3**	**1.4**
Feed rate per revolution (mm)	0.1	0.15	0.1	0.15
Tool revolution speed (rpm)	800	800	2000	2000
Drilling depth (mm)	2			

1) Effect of the tool revolution speed

In order to study the effect of tool revolution speed on the thrust cutting force and the drilling torque, we have considered results of the two numerical tests 1.1 and 1.3 of Table I. Fig. 3 shows the simulated curves of the thrust cutting force $F_z(t)$ and the drilling torque $M_z(t)$ for each tests. From this figure, we can see clearly the thrust force and drilling torque increase gradually with the increase of the tool revolution speed. Indeed, a part of the thrust cutting force depends on the force of penetration of the tool into the workpiece F_p. This force is due to the constant pressure exerted by the tool tip on the workpiece as the cutter moved down into the workpiece. According to [8] F_p is expressed by

$$F_p = (0.0032V_f^{\,3} - 1.825V_f^{\,2} + 374V_f - 9786)\,S\,, \tag{3}$$

where $V_f = f\,n$ is the feed-rate (mm/mn) in which f is the feed rate per revolution (mm/rev), n revolution speed of the tool (rpm) and *S* is the section of the extruded chips (mm²).

2) Effect of the feed rate per revolution

Fig. 4 shows the effect of the feed rate per revolution on thrust cutting force $F_z(t)$ and the drilling torque $M_z(t)$ relatively to tests 1.1 and 1.2 of table I. It is also clear that the thrust force and drilling torque increase gradually with the increase of the feed rate per revolution. Indeed, in addition to its favorable effect to increase the penetration force of the tool in the workpiece F_p, the feed per revolution has a main influence on the chips thickness generated during the cutting process. The increase in feed per revolution increases the chip thickness and consequently the values of cutting forces and drilling torque increase.

C. Effect of Tool Parameters

In the second companion tests, we propose to study the effect of the tool diameter and the tip angle on the thrust cutting force and the drilling torque. To achieve this objective, data in Table II have been considered.

TABLE II. SECOND TEST CAMPAIGN: EFFECT OF TOOL PARAMETERS

Cutting parameters				
Feed rate per revolution (mm)	0.1			
Tool revolution speed (rpm)	800			
Drilling depth (mm)	2			
Additional forced vibrations				
Mass of the vibratory system (g)	25			
Frequency of vibrations (Hz)	50			
Amplitude of vibrations (mm)	0.01			
Cutter geometry parameters (tungsten carbide tool K20)				
Helix angle (°)	32.5			
Number of teeth	2			
Radial rake angle (°)	10			
Clearance angle (°)	8.58			
Width of the chisel edge (mm)	0.16			
Test Number	**2.1**	**2.2**	**2.3**	**2.4**
Diameter (mm)	6.35	8.00	6.35	8.00
Tip angle (°)	136	136	120	120

1) Effect of the tool diameter

Two tool diameters (6.35 and 8 mm) are considered to study their effect on thrust cutting force and drilling torque. Results of this simulation (Fig. 5) show that both the thrust force and torque increase when the tool diameter increases. The time required for the release of the tip of the tool also increases. This can be attributed to the height of the tip of the tool defined by $a_p = \frac{D}{2\tan(\kappa)}$ which increases when the tool diameter increases. Consequently, the involved number of the elementary cutting disks N_d is more important for a tool with *D* = 8 mm from a tool with *D* = 6.35 mm.

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2) Effect of the tool tip angle

Two tip angles (136 ° and 120 °) are considered to study their effect on thrust cutting force and drilling torque.

Results of this simulation (Fig. 6) show that the tip angle has not a significant effect on the maximum values of the thrust force and torque. However with a tip angle of 136 °, the thrust cutting force and torque reach their maximum value in a shorter cutting time than with a 120 ° tip angle. This can be attributed to the height of the tip of the tool defined by $a_p = \frac{D}{2\tan(\kappa)}$ which decreases when the tip angle increases.

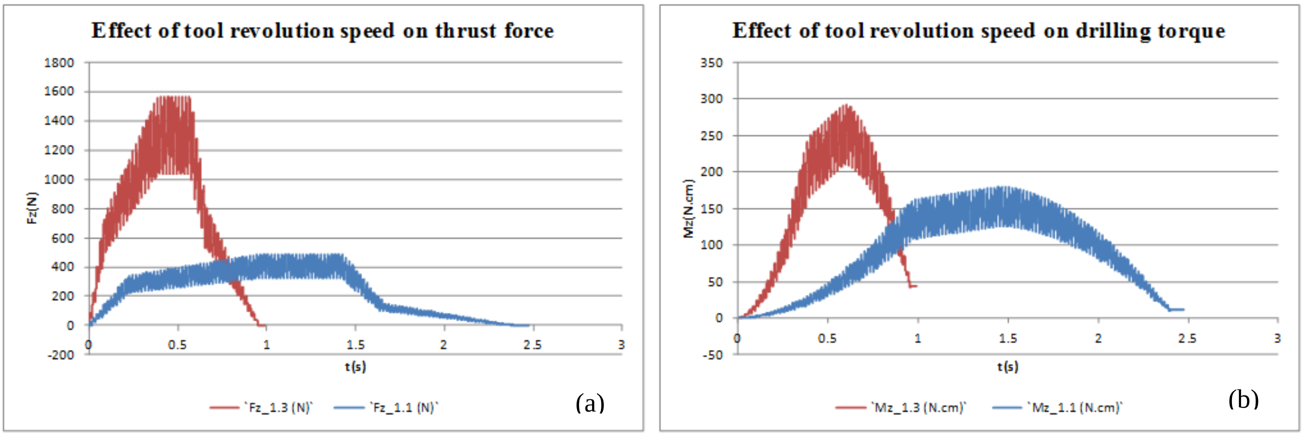

Figure 3. Effect of too revolution speed on thrust cutting force (a) and drilling torque (b)

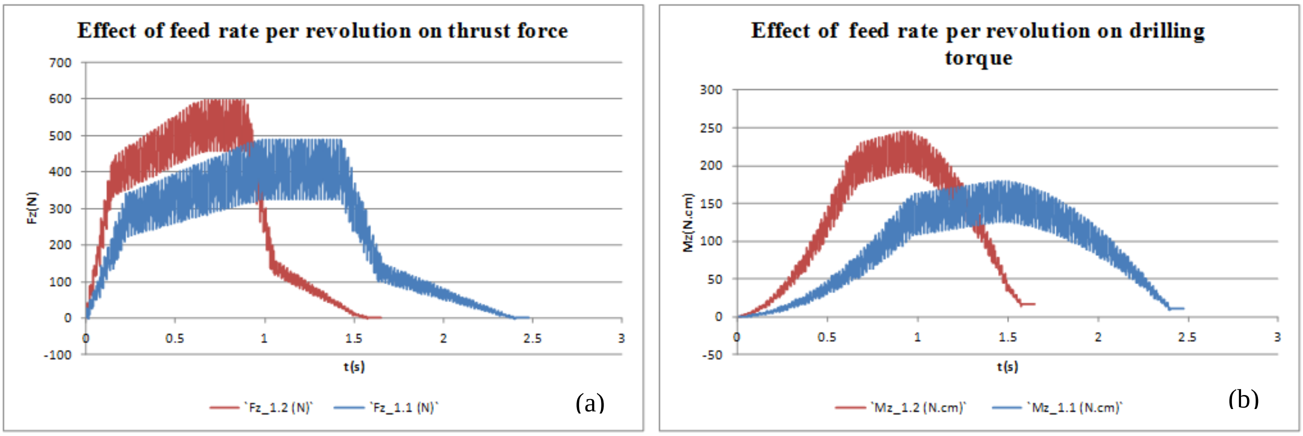

Figure 4. Effect of feedrate per revolution on thrust cutting force (a) and drilling torque (b)

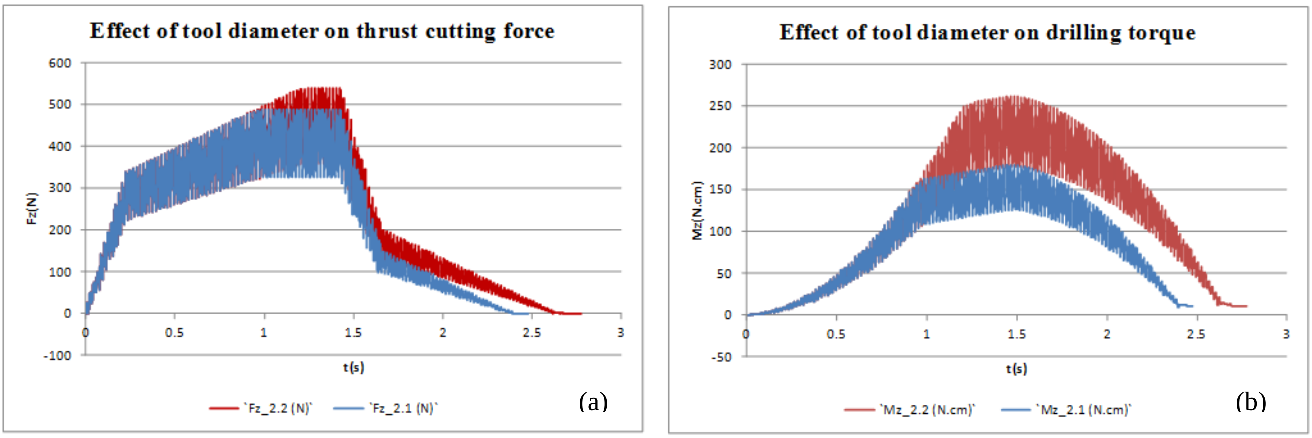

Figure 5. Effect of tool diameter on thrust force (a) and on drilling torque (b)

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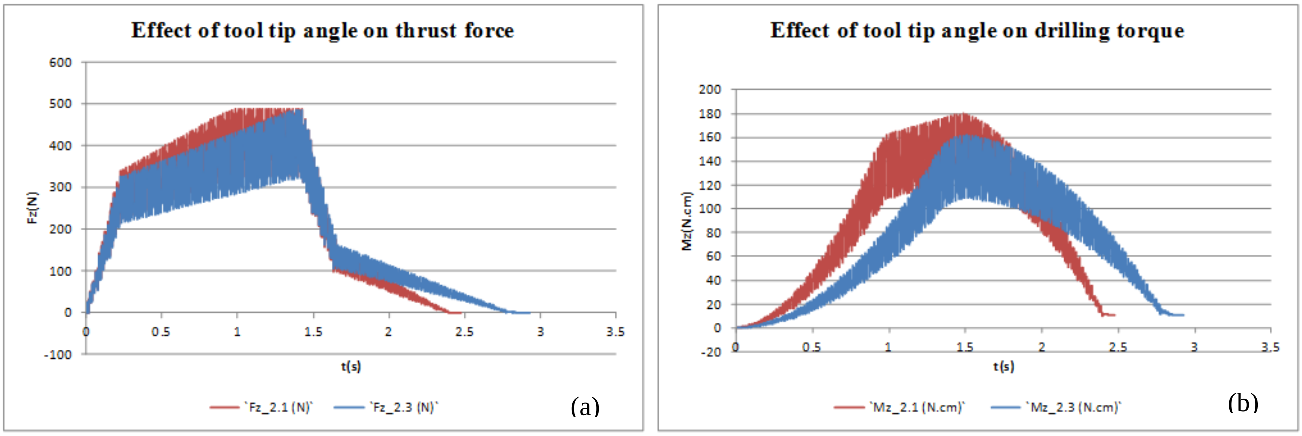

Figure 6. Effect of tool tip angle on thrust force (a) and cutting torque (b)

IV. CONCLUSION

In this paper, a model for prediction of thrust cutting force and torque during a drilling operation assisted by forced low-frequency vibration of titanium alloy Ti6Al4V is presented. The effect of additional forced vibration and of some tool parameters (diameter and tip angle point) and some cutting parameters (tool revolution speed and feed rate per revolution) on the thrust cutting force and drilling torque have been discussed. This discussion revealed that:

- The variation of the thrust cutting force and torque with an additional forced vibration takes place respectively around the cutting force and torque without additional vibration. The variation of the thrust cutting force can be a solution for good fragmentation and better chip evacuation.
- The maximum values of thrust cutting force and torque increase when the tool diameter / tool revolution speed / feed rate per revolution increase. The tip angle point has no great influence on the maximum values of the thrust force and torque.

Our future work is concerning the application of the model for the prediction of the thrust cutting force and torque during the drilling of multilayer materials. A series of drilling tests with different cutting conditions will be carried out in order to study their effects on the cutting force and the interlayer zone.

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Nawel Glaa graduated from the University of Versailles in 2013 with a master's degree in Dimensioning of Mechanical Structures in their environment. She obtained a PhD in Applied Mechanics from the polytechnic school of Tunis. The title of these topics is "Experimental and numerical analysis of CFRP / Al and CFRP / Ti multi-material drilling process". She is a member at the Mechanical Laboratory of Solids, Structures and Technological Development of the Engineering National High School of Tunis (ENSIT), University of Tunis (UT) - Tunisia.
She is a temporary assistant at the National School of Engineers of Carthage (ENICarthage)
Her research works has been published in International Journal of Advanced Manufacture.

Kamel Mehdi was graduated as a Mechanical Engineer from ENIS, Tunisia, in 1989. He received his Ph.D. degree in mechanical engineering in 1995 from INSA of Lyon, France, and his HDR diploma in 2008 from ENIS, Tunisia. His research interests are machining and manufacturing processes, concurrent engineering, and computer integrated design of mechanical systems. He is currently an Associate Professor in mechanical engineering at the Preparatory Institute for Engineering Studies El Manar (IPEIEM), University of Tunis EL Manar (UTM), Tunis, and he is a Researcher at the Mechanical Laboratory of Solids, Structures and Technological Development of the Engineering National High School of Tunis (ENSIT), University of Tunis (UT), Tunisia. His research works have been published in the International Journal of Advanced Manufacture Technology, International Journal of Mechanical Engineering and Robotics Research (IJMERR) Transactions of the ASME (Journal of Manufacturing Science and Engineering), International Journal of Vehicle Design (IJVD), Journal of Machining and Forming Technology (JoMFT), Int. Journal of Engineering Simulation (IJES), Journal of Decision Systems, Applied Mechanics and Materials, Advanced Materials Research (JDS), and Int. J. Machining and Machinability of Material and in many international conferences. He is member of the scientific committees of many national and international conferences in mechanical engineering.

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