THAI NGUYEN UNIVERSITY

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A STUDY ON VIBRATION ASSISTED DRILLING OF DEEP AND SMALL HOLES ON ALUMINUM ALLOYS

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SUMMARY OF DOCTORAL THESIS IN ENGINEERING

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Introduction

1. Motivation

Ultrasonic Assisted Machining (UAM) is a modern machining technique in which a high-frequency vibration (≥20 kHz) with low magnitude (in micrometer range) is supplemented to the relative movement between the cutting tool and workpiece during a machining process [1]. In this machining technique, the cutting tool or workpiece vibrates along one or multiple directions with respect to the cutting direction. The combination between this additional vibration movement and cutting direction leads to periodical changes of the contact between the cutting edge and workpiece. This results in the change of friction caused by the contacting between the cutting edge, workpiece and chip during machining, which in turn can reduce the cutting force, leading to the improvement of surface quality and machining accuracy and the increase in productivity and tool longevity. To this end, UAM is a new machining method, combining the traditional machining and ultrasonic machining.

Nowadays, UAM has been widely applied on almost various traditional machining processes such as milling, turning, drilling, etc. In addition, ultrasonic is integrated in some advanced manufacturing processes such as electric discharge machining (EDM) and laser beam machining (LBM) [2]. Recent studies have shown that UAM can provide advantages over traditional machining, for example, in cases of turning Ti-15333 alloys [3] and β-Ti alloys [4], milling Al2A12 [5], surface gridding in Ni-Rene77 [6], gridding Inconel 718 [7], EDM [8], etc.

Among traditional machining techniques, drilling is one of the most common methods which is used for making holes in solid materials. In general, a conventional machining process comprises drilling (30%), turning (20%), milling (16%), threading (15%), contouring (6%) and other kinds of machining (13%) [9]. Although having only two basic motions of transition and rotation, the essence of the drilling process is more complicated than other machining processes. During milling, turning and shaping, chip removal space is open. Hence, – the chip removal process is not constrained by geometry. However, in drilling process, because the chip removal space is close, the machining process is accompanied by the process of pushing chips out of the machined hole. In deep-hole drilling ($L/D \geq 5$) [10, 11], especially in the case of ductile materials, there are many difficulties in chip removal, which leads to decrease in productivity, quality and tool longevity. The smaller size the hole is, the narrower the chip removal space will become, causing more difficulty in chip removing process. Many technical methods have been used to improve drilling processes. For example, improving tool surface quality and texture, adopting advanced lubricating and cooling techniques [12], [13], [14], [15], low-frequency vibration assisted drilling [16], [17], [18] and peck-drilling have been investigated. However, they have not yet solved the problem of chip removal in deep-hole drilling, which is even more challenging when the diameter of the processed hole is small (less than 5 mm). Using a drill having a feeding-lubrication hole has contributed to improve chip removal, but it requires a complex structure design to carry and feed lubrication while the drill is rotating; it also leads to the high tool cost.

Ultrasonic Assisted Drilling (UAD) has been successfully applied on drilling difficult-to-machine materials. Compared to conventional drilling (CD), UAD method has been considered to be more superior. For instance, it improves chip removal process during drilling aluminum alloys without lubrication [19], [20], [21]; reducing cutting force and cutting temperature and improving longevity of cutting tools during drilling high strength and hardness materials [22], [23], [24], [25], [26]; decreasing the distortion of the workpiece, improving hole geometry accuracy [27], [28] and reducing burrs [29]; extending machining drilling possibilities for some difficult-to-machine materials [1], [30]

In micro-drilling, adding vibration helps reduce the axial force by about four times, increase tool longevity by about 20 times when drilling Al2017 holes with 20 μm in diameter [31], decease the average axial force by 60% when drilling holes having a diameter of 1 mm in PCB reinforced glass fiber material, etc.

Although many advantages of UAD over CD have been seen, according to several experts, there have not been investigations examining the efficiency of chip removal when applied UAD for deep-hole and small-hole drilling. Within national research community, there has not been any study on UAM either. Therefore, the present research aims to solve twofold current problems: (1) to investigate in establishing procedures of designing and manufacturing UAM processes in a systematic way, which would provide advice for national and regional research institutes in the field of UAM; (2) to examine the efficiency degree of imperilment in deep and small hole drilling when applied UAM, which will contribute new scientific knowledge of this cutting-edge field.

2. Aims, objectives and scopes of the present research

2.1. Research aims

The main aim of this research is to evaluate efficiency of the improvement in deep and small hole drilling when applied UAM. This includes the following details:

+ To design and manufacture drilling system with ultrasonic assistance and to establish an effective measuring system which can be easily applied in national and regional studies.

+ To evaluate the positive impact of ultrasonic vibration on deep drilling on aluminum alloys based on four criteria: productivity, axial force, torque and heat produced on the workpiece.

+ To develop a model describing the drilling torque as a function of drilling depth for the following purposes: (1) predicting the reachable drilling depth during continuous drilling and (2) improving the efficiency and possibilities in industrial applications.

2.2. Research objectives and scopes

The study focuses on cutting processes during deep and small hole drilling. The scope is limited to Al-6061 alloys, using high-speed steel drills with the diameters of 3 and 4 mm and the ratio $L/D \geq 8$. This investigation is conducted in a research laboratory equipped with ultrasonic assisted drilling facilities, which were designed, manufactured and operated based on the practical conditions.

3. Research methodology

The methods used in this study include design of experiments, applied statistical analysis and mathematical regression.

4. Scientific and application-oriented significances

4.1 Scientific significances

This research contributes several insights in machining, especially in deep and small hole drilling on aluminum alloys during UAM. Detail contributions are as below.

+ Validated the positive effects of ultrasonic on cutting mechanism and the chip removal process based on the criteria of the cutting force, torque and heat during drilling.

+ Confirmed that the adherence charateristics and stuck chip issues woud be the major causes which reduce the machinablity in deep drilling of soft materials such as aluminum and aluminum alloys.

+ Developed a mathematic model describing the relationship between the torque and the cutting depth during drilling. The model was experimental validated and then applied to predict the reachable drilling depth.

+ The results obtained from this research can be used as guidelines for further experimental studies in the field. It can also be good references for academic teaching and scientific researches.

4.2. Application-oriented significances

This research has successfully implemented the technique of deep- and small-hole drilling with ultrasonic vibration assistance. The achieved results can be applied in industry to enhance the deep and small-hole drilling processes, especially in mold and die machining.

5. The contributions of the present study

- This is the first time an experimental setup for UAM has been established, which is suitable for the facilities available in the country. This contribution would be a good beginning for further studies in this field in Vietnam.

- Several advantages of deep drilling with ultrasonic vibration assistance compared to conventional drilling have been evaluated through criteria including the productivity, drilling torque and axial force.

- A new mathematical model describing the drilling torque as a function of drilling depth in the exponential form was developed. The model is useful and convenient in comparing the drilling torque in different drilling processes. This would also be a significant contribution for further study in modelling and predicting the torque during deep drilling.

6. Thesis structure

Chapter 1. Literature review of vibration assisted machining.

Chapter 2. Fundamental theory of drilling with ultrasonic vibration assistance

Chapter 3. Design and implement experimental setup

Chapter 4. Experimental study in deep drilling with ultrasonic vibration assistance

Chaper 5. Develop the model describing the torque during deep drilling

CHAPTER 1. LITERATURE REVIEW OF VIBRATION ASSISTED MACHINING

1.1 Introduction

1.2 Important terms in ultrasonic vibration

1.2.1 Ultrasonic vibration

1.2.2 Methods of ultrasonic vibration generation

1.3 Application of ultrasonic vibration in machining

1.3.1 Ultrasonic machining

1.3.2 Rotary ultrasonic machining

1.3.3 Ultrasonic assisted machining

1.4 Review of experimental studies on UAD

1.4.1 Effect of UAD on chip formation

1.4.2 Effect of UAD on thrust force

1.4.3 Effect of UAD on torque

1.4.4 Effect of UAD on cutting temperature

1.4.5 Effect of UAD on machining quality

1.4.6 Effect of UAD on tool life

1.4.7 Effect of UAD on productive rate

1.5 Review of theoretical studies on UAD

1.6 Major problems in machining of aluminum alloys

1.6.1 Machinability of aluminium alloys

1.6.2 Machinability of aluminium alloys in drilling

Chapter conclusions

Summaries from literature review

Drilling with ultrasonic vibration assistance brings about positive effects compared to traditional drilling such as: reducing the axial force, torque and cutting heat, increasing tool longevity, improve productivity and quality of machining, etc. However, almost studies about drilling with ultrasonic vibration assistance have only been done in drilling normal hole, which has depth-to-diameter ratios L/D smaller than 5.

The increasing number of publications on international journals about drilling with ultrasonic vibration assistance in recent years reflect the importance of this research filed. However, for the best of the author knowledge, there has rarely found any publication from local studies.

Twist drills are most commonly used (about 70%) in industry for deep drilling. These drills are also used in almost studies on drilling with ultrasonic vibration assistance.

Drilling aluminum alloys, especially in the cases of small and deep holes, is one of the most significant topics of many technical solutions. For example, using technical deep drills or drilling disrcretly with many steps, in order to improve the drilling process because the machinability of aluminum alloys is low. Drilling with ultrasonic vibration assistance has another superior advantage over other machining methods, which is the possibility of without the need to use lubrication.

Research scope determination

From the critical points above, the author defined the research scope as following: Applying the technique of ultrasonic vibration assisted drilling small and deep holes on Al-6061 material, using high-speed steel twist drills without lubrication.

Scientific hypothesis

Ultrasonic vibration is added to the drilling process to reduce friction produced by contact between chips and spiral path and between chips and wall holes, therefore, improving the chip removal conditions. In order to validate this hypothesis, a set of criteria is proposed, which includes the cutting temperature of the workpiece, machining productivity, axial force and torque during deep drilling.

CHAPTER 2. THEORY OF DRILLING WITH ULTRASONIC VIBRATION ASSISTANCE

2.1 Introduction

2.2 Ultrasonic Assisted Drilling

2.2.1 Principle of ultrasonically assisted drilling

2.2.2 Mechanism of ultrasonically assisted drilling

2.2.3 Dynamic of ultrasonically assisted drilling

2.2.4 Mechanism of cutting force reduction in ultrasonic assisted drilling

2.3 Thrust force and torque in drilling

2.3.1 Thrust force and Torque independent of the drilling depth

2.3.2 Thrust force and Torque dependent of the drilling depth

Chapter conclusions

This chaper presents the theory of the drilling with ultrasonic vibration assistance. In addition to advantages of UAD shown in chapter 1, chapter 2 presents the essence of UAD by analyzing a model and formulas describing the movement of the drill. The difference in kinematics between UAD and CD is elaborated via examining the kinematics model of machining with the presense of the axial force.

The mechanism creating the advantages of UAD are as following:1) When supplemening vibration to drilling process, the thickness of chips is altered, leading to the decrease in the cutting force; 2) reducing the friction produced at the contact between chips, the rake face and the flank of the cutting tool and the machined surface.

The resuls obtained from analyzing and manipulating formulas for the axial force and torque in some conventional handbooks and in some recent publications present the advantages of UAD based on the criterion of reducing the axial force will be presented in chapter 4. The development of a mathematical model describing the axial force and torque during deep drilling will be shown in chapter 5.

Literature review also helps propose the experimental setup in chapter 3 and experimental analysis in chapter 4.

CHAPTER 3. DESIGN AND MANUFACTURE EXPERIMENTAL SETUP

3.1. Introduction

3.2 Major components of the UAM system

3.2.1 Ultrasonic generation

3.2.2 Ultrasonic transducer

3.2.3 Ultrasonic horn

3.3 Design of the UAD system

3.3.1 Structural design

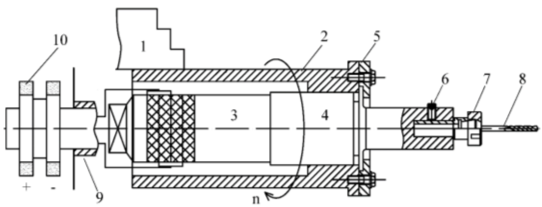


Figure 3.8 Structure of the ultrasonic vibratory unit with drill bit

3.3.2 Component design

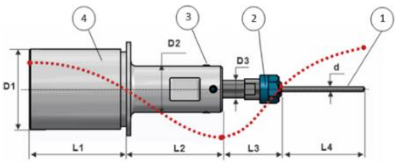


Figure 3.9 The vibratory unit and main dimensional parameters

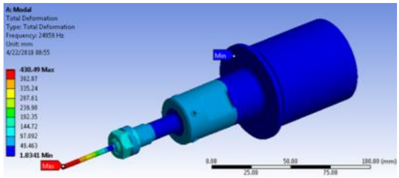


Figure 3.10 A modal analysis of the horn assembled with the tool bit

3.4 Manufacture, assembly and adjust the experimental setup

3.4.1 Manufacture and assembly the system

3.4.2 Validate by impedal analyzer

3.4.3 Validate by digital oscilloscope

3.4.4 Measure vibration amplitude

3.4.5 Experimental validation of the UAD system

3.5 Experimental setup

3.5.1 The aim and method of experiments

3.5.2 Experimental devices

3.5.3 Measurement and data acquisition

Chapter conclusions

This chaper presents major steps from designing, manufacturing, measuring and evaluating the efficiency of the UAD system. Some results obtained are as below.

The UAD system located on a lathe machine, in which the drill rotates and vibrates simultaneously, was successfully designed and realized.

A practical solution to carry out the resonant frequency of the UAD by a wave-detecting device conneted to a computer was presented.

Compared to a common used device (HIOKI3532-50 which costs about 3500 USD), this solution offered a much cost-effective with more than 10 times cheapper, while the measured errors were as small as from 1% to 2%.

The UAD system manufactured was used for experimental study which will be presented in chapter 4.

CHAPTER 4. EXPERIMENTAL STUDY OF VIBRATION ASSISTED DEEP DRILLING

4.1 Introduction

4.2 Experimental

4.2.1 Experiments with contant feeding force

Bảng 4.1 The parameters for experimental tests

Spindle speed (rpm)	1250
Feed force conditions (kg)	6; 9; 12
Feed force value (measured in N)	58,86; 88,29; 117,72
Drill diameter (mm)	3
Workpieces dimensions (mm)	10 x 10 x 40
Cutting condition	Dry
Vibration amplitude (%)	0; 100

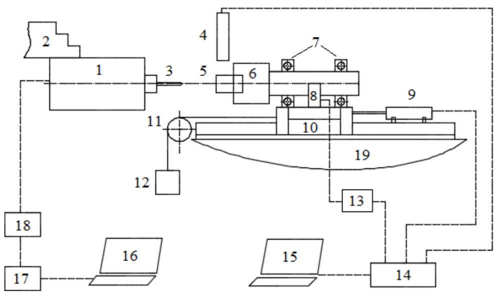


Figure 4.1 Experimental schema

4.2.2 Experiments with contant feeding speed

Table 4.2 The parameters for experimental tests

Spindle speed (rpm)	1000; 1250; 1500
Feed rate (mm/rev)	0,05; 0,065; 0,085
Drill diameter (mm)	3; 4
Maximum of depth drilling (mm)	30
Cutting condition	Dry
Vibration amplitude (%)	0; 50; 100

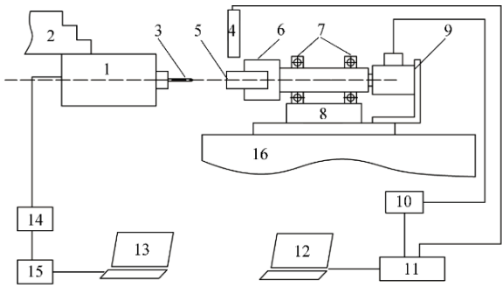


Figure 4.3 Experimental schema

4.3 Advantages of deep drilling with contant feeding force

4.3.1 Material removal rate

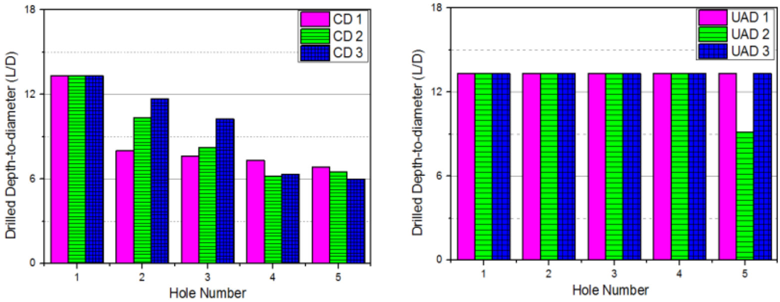
Denote the relative displacement of the workpiece respecting to the tool bit as L_k, the material removal rate (MRR) after a cutting time T_k can be express as:

$$MRR_k = \frac{\pi D^2}{4}\frac{L_k}{T_k} \qquad (4.1)$$

Table 4.1 Comparative data of material removal rate between UADs and CDs

Feed force (N)	$\overline{MRR}$(UAD) (mm^3/s)	$\overline{MRR}$(CD) (mm^3/s)	$\frac{MRR(UAD)}{MRR(CD)}$	Standard deviation of MRR for UADs	Standard deviation of MRR for CDs
58,86	1,01102	0,43609	2,32	0,06297	0,07153
88,29	0,90751	0,61662	1,47	0,06878	0,08986
117,72	1,56158	1,04944	1,49	0,14563	0,15651

4.3.2 Ability to drill depth holes



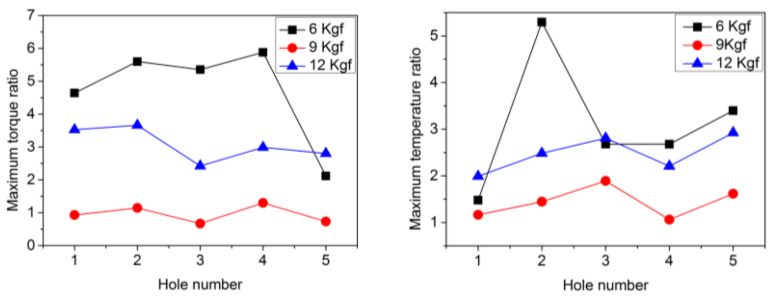
(a) (b)

Figure 4.7 Deep holes: reachable L/D ratios of CD holes (a), reachable L/D ratios of UAD holes (b)

4.3.3 Torque and temperature

In order to have a quantity comparison, the maximum value of torque and workpiece temperature during drill progress were taken. Ratios of torque between CDs and that of UADs at the same hole number were then calculated out. Ratios of temperature were carried out in the same way.

$$R_{T_{ij}} = \frac{T_{max\_CD_{ij}}}{T_{max\_UAD_{ij}}} \quad \text{và} \quad R_{t^0_{ij}} = \frac{t^0_{max\_CD_{ij}}}{t^0_{max\_UAD_{ij}}}$$



(a) (b)

Figure 4.9 Maximum torqure ratio (a) and maximum temperature ratio (b) respect to hole number

4.3.4 Explanation of the effectiveness of UAD

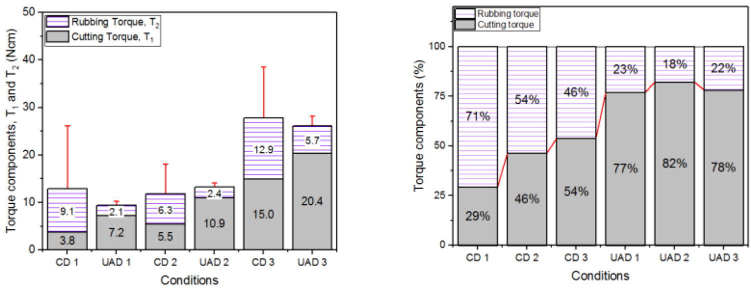
The total drilling torque, *T* can be considered as a sum of three components: $T=T_1+T_2+T_3$ where T_1 is the cutting torque, considered to be constant, i.e. does not depend on the drilled depth. T_2 is the component that continuously increases. This torque component is required to evacuate the chips, hereafter named the rubbing torque. The component T_3 is randomly fluctuated and thus assumed as the torque needed to overcome the stick-slip of the chips with the flutes and the hole wall. In this study, T_3 was named the stick-slip torque.

A hypothesis which can be used to explain the reason for advantages of UAD in deep drilling is proposed as following: the superimposed ultrasonic vibration can reduce friction induced among chips, the tool fultes and the hole wall and thus reduce the torque (induced by friction) in deep drilling. In order to make it more convenient in analysis processes, a model of the torque should be developed. The dependent of the chip evacuation torque on the hole depth was developed in several previous studies can be expressed [57], [118], [119] as:

$$T_{chip} = A.e^{B(L/D)} \qquad (4.2)$$

In this study, the chip evacuation is divided into two components Tchip=T2+T3 where only T2 is modeled as an exponential function:

$$T_2 = A.e^{B(L/D)} \qquad (4.3)$$



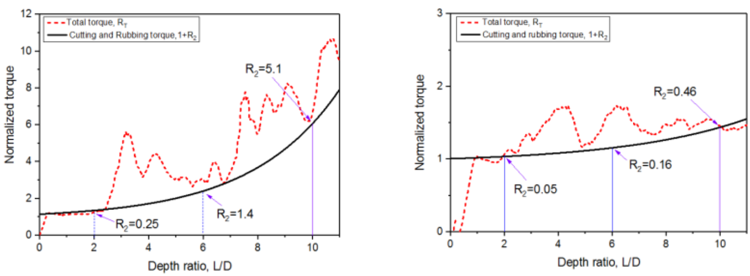
(a) (b)

Figure 4.17 Stacked experimental data of the cutting and rubbing components (a) in average values and (b) proportion of each component

In order to confirm the UAD's advantages, the growing rate of the torque when the depth increases was evaluated. The total torque and the torque components are normalized by dividing by the cutting torque. In order to make it easier to compare, let introduce three normalized torque components as:

$$R_T = \frac{T}{T_1};\ R_1 = \frac{T_1}{T_1} = 1; R_2 = \frac{T_2}{T_1};\ R_3 = \frac{T_3}{T_1} \qquad (4.4)$$

where R_T, R_2 and R_3 represent for the normalized values of the total torque, rubbing torque and stick-slip torque, respectively. It would be noted that, cutting torque is the only useful component of a cutting process. One operation is more effective than the other if the former has smaller torque ratios than the later.



(a) (b)

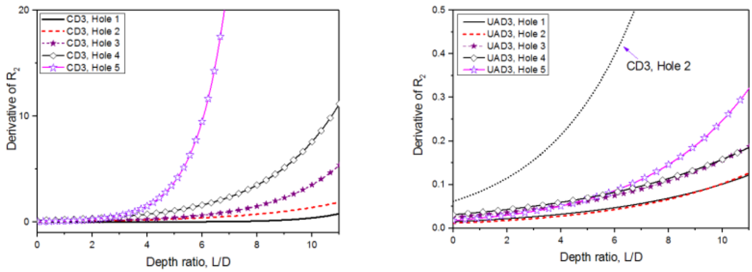
Figure 4.18 Normalized torque components of (a) CD and (b) UAD

Another brilliant aspect of UADs for deep drilling was that, UAD can decelerate the growing rate of the rubbing torque. The growing rate, *K* of a function *y=y(x)* can be calculated as:

$$K = \frac{dy}{dx} \tag{4.5}$$

$$K_{R2} = \frac{d}{d(L/D)}\left(\frac{Ae^{BL/D}}{T_1}\right) = \frac{AB}{T_1}e^{BL/D} \tag{4.6}$$

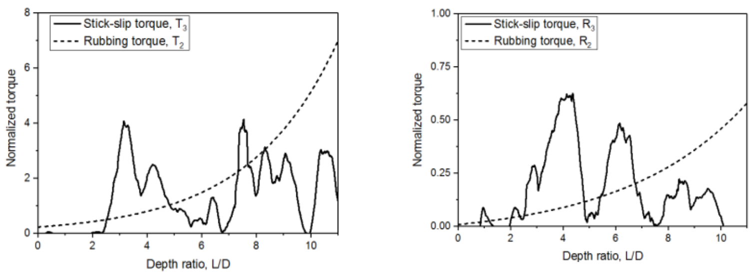
The growing rate of the chip evacuation torque is depicted in Figure 4.19.



(a) (b)

Figure 4.19 Growing rate of normalized torque component of (a) CD and (b) UAD

The fluctuated amplitude of T3 in UAD and in CD are presented in Figure 4.20.



(a) (b)

Figure 4.20 Variations of the normalized stick-slip and rubbing torques of (a) CD and (b) UAD

4.4 Advantages of UAD in deep drilling with contant feeding speed

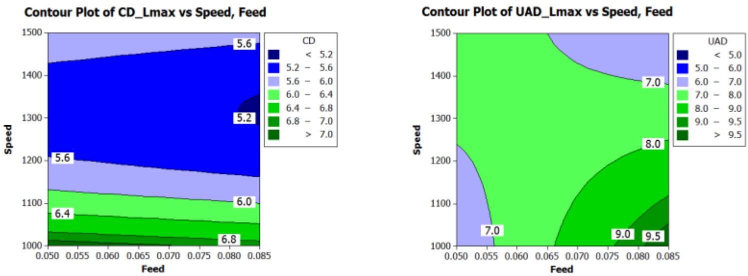
4.4.1 Thrust force and tởrque

4.4.2 Cutting torque

Table 4.6 Results of Paired T-Test obtained from Minitab®

Paired T for T_{CUT}_CD – T_{CUT}_UAD				
	N	Mean	StDev	SEMean
T_{CUT}_CD	27	15,826	3,578	0,689
T_{CUT}_UAD	27	11,989	3,825	0,736
Difference	27	3,837	1,662	0,320
95% CI for mean difference: (3.179; 4.494) T-Test of mean difference = 0 (vs not = 0): T-Value = 11.99, P-Value = 0.000				

4.4.3 Critical depth



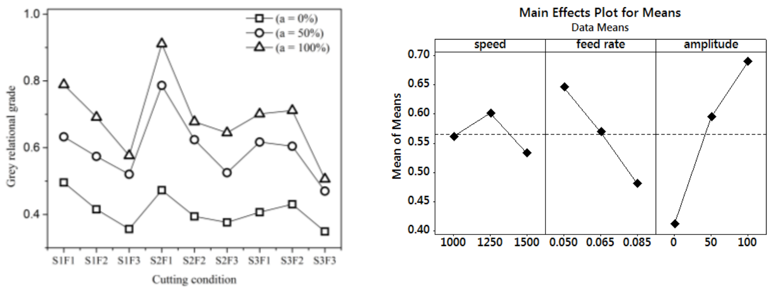
(a) (b)

Figure 4.25 Contour plots of critical depth in (a) CD tests and (b) UAD tests

The critical torque data have been collected from experiments ranged from 330 to 370 Ncm. A safety factor of 5 was chosen in this study, making the allowance threshold torque, Ta, of 70 Ncm. Figure 4.25, the critical depth obtained from CD tests ranged from 5.2 to 6.8 times of the hole diameter, while that from UADs ranged from 6 to 9.5 times of the hole diameter.

4.5 Selection of the cutting parameters

The optimal level for each of three input parameters, including the cutting speed, feed rate and the vibrational amplitude, can be determined as the highest value in the investigated range, as shown in Figure 4.27.



(a) (b)

Figure 4.27 Grey grades with respects to cutting conditions (a) and Factor effects on grade values (b)

Chapter conclusions

This chapter presented an experimental study to examine the advantages of ultrasonic assisted drilling (UAD), focusing on the ability of UAD to safety lengthen the critical depth in small and deep drilling. The experimental plan and the results have been implemented using the theory of experiment design, applying CCD and Grey-Taguchi methods.

From this chapter, the following remarks can be concluded:

Ultrasonic assisted drilling can reduce the cutting torque by 25% compared to conventional drilling. Moreover, UAD can provide a much higher range of the hole depth which can be safety drilled.

The ultrasonic assistance can be also combined with grooving technique and/or peck drilling to further develop in deep drilling technique.

The combination of Taguchi design of experiment and grey relational analysis (TGRA) would be a useful but not very complex tool for multi-objective optimization of the operational parameters in ultrasonic assisted deep hole drilling;

It has been revealed that, ultrasonic vibration amplitude, feeding rate and cutting speed are three essential factors providing major effects on the forces and torques in the ultrasonic assisted deep hole drilling;

The optimum condition was predicted by TGRA and verified by confirmation experiments. The results showed that TGRA would be a very promising to address the multi-response optimization problems in practical machining fields.

CHAPER 5. DEVELOP THE MODEL DESCRIBING THE TORQUE DURING DEEP DRILLING

5.1 Introduction

5.2 Previous models

According to Jeffrey C. Mellinger et al. [57], the total torque in drilling can be expressed as:

$$M_{total} = M_{cut} + n_f \cdot M \tag{5.1}$$

and

$$M = \frac{R\mu_W S_W F_c(0)}{B}\left(e^{(kBD/A_0)z} - 1\right) \tag{5.1}$$

Such model has been developed where the model parameters are fitted by regression technique in logarithmic form of rotation speed and feed rate as following [58]:

$$\ln(\mu_W) = a_0 + a_1 \ln(f) + a_2 \ln(N) + a_3 \ln(f)\ln(N) \tag{5.2}$$

Han et al. (2018) [124] proposed an improved model with only two parameters as:

$$T_{ch}(z) = K_{tch}\left(e^{K_{ch} \cdot z} - 1\right)\frac{D}{2} \quad (5.3)$$

5.3 The new model

In this study, the total torque was considered as a sum of three components as following:

$$T = T_1 + T_2 + T_3 \quad (5.4)$$

5.3.1 The cutting torque

Cutting torque, T_1 can be expressed as [125-127]:

$$T_1 = C.f^{(1-\alpha)} D^{(2-\alpha)} \quad (5.5)$$

Table 5.2 Calibrated results of the coefficient C in Equation (5.6)

D(mm)	Cutting condition	Value	Statistics Adj. R-Square
4	CD	0,15475	0,99869
	UAD	0,12156	0,99863
3	CD	0,1502	0,97633
	UAD	0,1209	0,9032

5.3.2 The chip-evacuation torque

The chip evacuation torque, T_2 is expressed as a function of the drill depth:

$$T_2 = A\left(e^{(A \cdot z)} - 1\right) \quad (5.6)$$

where A is the coefficient determined by calibration tests, *z* is the drilled depth.

The growing rate of the torque can be expressed as:

$$\frac{dT_2}{dz} = \frac{d}{dz}\left[Ae^{(A \cdot z)} - A\right] = A^2 e^{(Az)} \quad (5.7)$$

Table 5.4 Paired t-test for difference of the chip-evacuation coefficient, A between CDs and UADs

D (mm)	Mean	StDev	SE Mean	95% Lower Bound for μ_difference	T-Value	p-Value
3	0,1040	0,0728	0,0140	0,0801	2,43	0,011
4	0,1190	0,0580	0,0137	0,0952	2,12	0,024

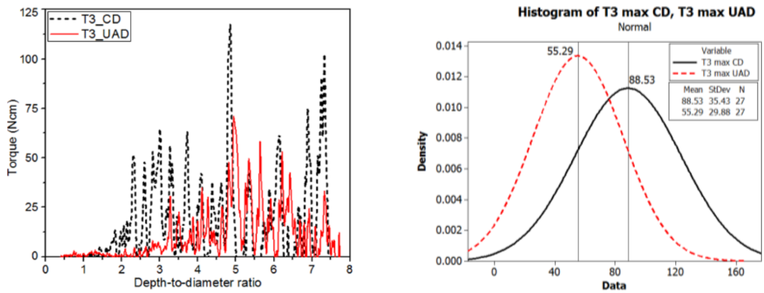
Where the factor A depends on the rotation speed and feeding rate. Such dependence can be expressed as a logarithmic funtion as [57, 128]:

$$\ln A = B * x \tag{5.8}$$

$$B = [a_0 \quad a_1 \quad a_2 \quad a_3] \tag{5.9}$$

$$x = [1 \quad \ln n \quad \ln f \quad \ln n \ln f]^T \tag{5.10}$$

5.3.3 The stick-slip torque



(a) (b)

Figure 5.8 (a) A couple of CD and UAD stick-slip torques and (b) probability of the maximum values of stick-slip torques

Table 5.6 Estimation for Paired Difference

D (mm)	Mean	StDev	SE Mean	95% CI for μ_difference	T-Value	P-Value
3	33,25	42,21	8,12	(16.55; 49.94)	1,75	0,091
4	34,3	51,6	12,2	(8,6; 59,9)	2,82	0,012

Chapter conclusions

This chapter presents results of developing a model to describe the torque induced during deep drilling. In the previous models found in literatures, the torque during drilling was divided into two components: the cutting torque and the chip removal torque. The variation of the latter is usually neglected by rounding signals by averaging values or by filtering signals. In the current study, the chip removal torque is further separated into two components: the chip removal torque and stick-slip torque. The latter is the variation which was usually neglected in the previous studies.

The results from taking into account the stick-slip torque show that the new model gives a better agreement with experimental data (R^2 values in various models are greater than 0,9). The stick-slip torque is significally higher than the cutting torque. Therefore, neglecting this component as shown in the prevous studies can lead to the inaccuracy of scientific results.

Compared to the previous model of describing the chip removal torque which has many parameters, the model proposed in the current study, which has only one parameter, makes it much easier to compare drilling processes with each other, leading to easier pointing out the advatanges of UAD over CD during deep drilling.

Conclusions

This thesis present a deep study on UAD on aluminum alloys and achieved several results as below.

Contributed to supplement knowledge about applying UAD in deep drilling.

Established successfully an experimental setup of UAD which allows to conduct experiments with good accuracy.

Evaluated the positive effects of UAD on deep drilling.

+ The experimental results with constant feeding force provided important remarks: compared to CD, the productivity of UAD was as higher as from 1,47 to 2,32 times; the torque produced at the depth L/D = 10 was 33 times lower; the maximum cutting temperature was 5 times lower than that in conventional drilling;

+ The experimental results with constant feeding speed provided the following remarks: compared to CD, in UAD the cutting force was reduced by 25%; the safe drilling depth increased by 1,4 times. It has also been found that the amplitude of vibration had a significant effect on the axial force and torque in the case of UAD.

The results pointed out that the vibration amplitude had the most important effect on the axial force and torque during UAD in deep drilling.

In this study, a new model describing the torque in deep drilling was successfully developed. The new model consists of three components: the cutting torque, the chip removal torque and the stick-slip torques.

In this study, the empirical factor C in the formula of cutting force T_1 for both cases of UAD and CD of Al-6061, using a high-speed steel cutting tool in the same cutting conditions and machnining parameters, was practically validated as below.

$$T_1 = C.f^{(1-\alpha)} D^{(2-\alpha)}$$

In the case of CD: C=0,1502 and C=0,1547 are corresponding to the drill diameters of 3 and 4 mm, respectively. In the UAD case: C=0,1209 and C=0,12156 are corresponding to the same drill diameters.

+ The formula to define the chip removal torque T_2 was expressed as below.

$$T_2 = A\left(e^{(A \cdot z)} - 1\right)$$

The research also defined the empirical factors which allow to determine A factor in the models for UAD and CD, with specific parameters, which can be based on to predict the chip removal torque at a z depth.

The results of comparision from the model showed that UAD reduced the cutting torque by 1,25 times, the chip removal torque by 4 times at the depth L/D=10. The stick-slip torque was smaller and the distribution range was torwards the miminum value more than CD.

The proposal for future reseach

Conduting experiments to evaluate and compare UAD and CD on different materials.

Define the effects of vibration parameters on the machining process, wearing mechanism, tool longevity and machnining quality in UAD.

Develop the model predicting the chip removal torque and descrete silding torque.

Scrutinize the mechanism of friction during chip removal, develop the model describing in detail the mechanism of reducing friction during chip removal from which an improved model can be developed for this important torque component.

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