UNIVERSITI PUTRA MALAYSIA

EXPERIMENTAL AND NUMERICAL INVESTIGATION ON FRICTION DRILLING OF DIFFICULT-TO-MACHINE MATERIALS

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By

SHAYAN DEHGHAN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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DEDICATIONS

To all of my love;

My Father & My Mother

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy.

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February 2019

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Faculty : Engineering

Friction drilling is a non-conventional hole-making process that utilizes a rotating conical drilling tool to penetrate workpiece and create a hole by forming a bushing without generating chip. In metallurgy, difficult-to-machine materials are defined as materials which have great toughness, high work-hardening and low thermal conductivity. Since the difficult-to-machine materials are receiving increasing attention in extreme applications, friction drilling offers a great potential for product fabrication. However, the major challenge of friction drilling on difficult-to-machine materials is the difficulty of machining that leads to poor friction drilling performance and short tool life. In this study, the friction drilling on difficult-to-machine materials of stainless steel AISI304, titanium alloy Ti-6Al-4V and nickel-based alloy Inconel718 using drilling tool of tungsten carbide was experimentally and numerically investigated. Experimental results revealed that the thermal and mechanical properties of work-materials, spindle speed and feed rate have great influence on the formation of bushing and tool life. To achieve maximum number of acceptable drilled-holes, the optimum process parameters for AISI304 are spindle speed 1000 rpm and feed rate 105 mm/min, for Ti-6Al-4V are spindle speed 1000 rpm and feed rate 145 mm/min, and for Inconel718 are spindle speed 1500 rpm and feed rate 145 mm/min. The maximum frictional heating is generated at bushing completion stage, where the conical region of drilling tool is contacted to drilled hole-wall. The higher thrust force was occurred in initial contact between drilling tool and workpiece, and consequently the circular grooves and work-material adhesion have proven that abrasive and adhesive wear occurred on center and conical regions of drilling tool, respectively. The maximum abrasive wear, adhesive wear and oxidative wear are occurred on drilling tools which drilled AISI304, Ti-6Al-4V and Inconel718, respectively. The developed numerical model can well represent the real process of friction drilling, and stress and temperature distributions on workpiece and drilling tool. It also can effectively demonstrate the heating distribution on workpiece, material softening and bushing formation. The numerical results indicated that severe stress occurs at the tool contact surface and adjacent region in the initial penetration. The inverse relationship between stress and temperature demonstrate the phenomenon of frictional heating and softening of the work-material in friction drilling which forms the bushing. Furthermore, the high plastic strain occurs on the hole-wall, which is the contact surface between drilling tool and work-material and it depends on the tool movement along the drilling path. The main contribution of this study is determining the effect of process parameters on drilling tool performance, bushing formation quality, thrust force and tool wear for friction drilling of difficult-to-machine materials with approach to improve friction drilling performance and reduce tool wear. Moreover the developed finite element modeling can provide a prediction for friction drilling process. In overall, this work demonstrated the behaviors of chip-less friction drilling on difficult-to-machine materials that can offer a great potential for a new product design and manufacturing.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah.

PENYIASATAN EKSPERIMEN DAN BERANGKA DALAM PENGGERUDIAN GESERAN BAHAN SUKAR-UNTUK-DIMESIN

Oleh

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Penggerudian geseran adalah proses pembuatan-lubang bukan-konvensional yang menggunakan alat gerudi kon berputar untuk menembusi bahan kerja dan menghasilkan lubang dengan membentuk sesendal tanpa menghasilkan cip. Dalam metalurgi, bahan sukar untuk mesin ditakrifkan sebagai bahan yang mempunyai ketangguhan yang tinggi, pengerasan kerja yang tinggi dan kekonduksian terma yang rendah. Disebabkan bahan sukar-untuk-dimesin menerima perhatian yang semakin meningkat dalam aplikasi ekstrem, penggerudian geseran menawarkan potensi besar untuk fabrikasi produk. Walau bagaimanapun, cabaran utama penggerudian geseran pada bahan sukar-untuk-dimesin adalah kesukaran pemesinan yang membawa kepada prestasi penggerudian geseran yang tidak lemah dan hayat alat yang pendek. Dalam kajian ini, penggerudian geseran pada bahan sukar-untuk-dimesin keluli tahan karat AISI304, aloi titanium Ti-6Al-4V dan aloi berasaskan nikel Inconel718 menggunakan alat gerudi tungsten carbide disiasat secara eksperimen dan berangka. Keputusan eksperimen menunjukkan bahawa sifat terma dan mekanikal bahan kerja, kelajuan gelendong dan kadar suapan mempunyai pengaruh yang besar terhadap pembentukan sesendal dan hayat alat. Untuk mencapai bilangan maksimum lubang gerudi yang boleh diterima, parameter proses optimum untuk AISI304 adalah kelajuan gelendong 1000 rpm dan kadar suapan 105 mm/min, untuk Ti-6Al-4V adalah kelajuan gelendong 1000 rpm dan kadar suapan 145 mm/min, dan untuk Inconel718 adalah kelajuan berputar 1500 rpm dan kadar suapan 145 mm/min. Pemanasan geseran maksimum dijana pada peringkat penyiapan sesendal, di mana kawasan kon pada alat gerudi bersentuhan dengan dinding-lubang yang digerudi. Daya tujahan yang lebih tinggi telah berlaku dalam sentuhan awal antara alat gerudi dan bahan kerja, dan seterusnya alur bulat dan lekatan bahan kerja telah membuktikan bahawa haus melelas dan melekat masing-masing berlaku di kawasan pusat dan kon pada alat gerusi. Haus melelas, melekat dan

pengoksidaan maksimum masing-masing berlaku pada alat gerudi yang menggerudi AISI304, Ti-6Al-4V dan Inconel718. Model berangka yang dibangunkan dapat mewakili proses sebenar penggerudian geseran, dan distribusi tekanan dan suhu pada bahan kerja dan alat gerudi. Ia juga dapat menunjukkan distribusi pemanasan secara berkesan pada bahan kerja, pelembutan bahan dan pembentukan sesendal. Hasil berangka menunjukkan bahawa tekanan yang teruk berlaku pada permukaan alat dan rantau bersebelahan dalam penembusan awal. Hubungan songsang antara tekanan dan suhu menunjukkan fenomena pemanasan geseran dan pelembutan bahan kerja dalam penggerudian geseran yang membentuk sesendal. Selain itu, terikan plastik yang tinggi berlaku pada dinding-lubang yang merupakan permukaan sentuhan antara alat gerudi dan bahan kerja dan ianya bergantung kepada pergerakan alat di sepanjang jalan penggerudian. Sumbangan utama kajian ini adalah menentukan kesan parameter proses pada prestasi alat gerudi, kualiti pembentukan sesendal, daya dorong dan haus alat untuk penggerudian geseran pada bahan sukar-untuk-dimesin dengan pendekatan untuk meningkatkan prestasi penggerudian geseran dan mengurangkan haus alat. Selain itu pemodelan elemen terhingga yang dibangunkan untuk penggerudian geseran dapat memberikan ramalan untuk penggerudian geseran proses. Secara keseluruhannya, kerja ini menunjukkan tingkah laku penggerudian geseran tanpa-cip pada bahan sukar-untuk-dimesin yang boleh menawarkan potensi besar untuk reka bentuk dan pembuatan produk baru.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philoshophy. The members of the Supervisory Committee were as follows:

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ALE	Arbitrary Lagrangian Eulerian
BUE	Built-up Edge
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CNC	Computer Numerical Control
DOE	Design of Experiment
EDS	Energy Dispersive X-Ray Spectroscopy
FCAR	Friction Contact Area Ratio
FEM	Finite Element Method
FSW	Friction Stir Welding
HAZ	Heat Affected Zone
LSC	Least Squares Circles
MCC	Minimum Circumscribed Circle
MIC	Maximum Inscribed Circle
MZC	Minimum Zone Circle
PVD	Physical Vapor Deposition
R&D	Research and Development
SEM	Scanning Electron Microscope
SFW	Spot Friction Welding

CHAPTER 1

INTRODUCTION

1.1 Background and Motivation

The fact that hole-making process is one of the most important operations in industry is undeniable. Friction drilling is a green non-traditional hot-shear machining technology, that is used for sheet metal hole making by friction, (Streppel & Kals, 1983). During this process the temperature increases, subsequently the material structure becomes soft and bushing is formed with a thickness of about three times larger than original workpiece thickness. The contribution of friction drilling is to increase the effectiveness of thread length and screw coupling, which is used for load clamping in joining application (Miller & Shih, 2006; Miller et al., 2005). Since friction drilling is a clean and chipless process with no cutting fluids, this hole-making process is defined as a green manufacturing process. Hence, it can fulfill the needs of dry machining.

Joining devices to sheet metal, tubing, or thin-walled profiles in an effective way is a manufacturing challenge in most of the industries. Friction drilling can simplify the joining process (Miller & Shih, 2006). It has some significant advantages including fast process, no additional components, cost effective, simplified production, high quality and green manufacturing (Ozek & Demir, 2013b). Friction drilling is an excellent alternative for hole stamping and nut welding, which needed for attaching a device to sheet metal in order to reliability and process cost. Complicated robot used for nuts welding to sheet metal is replaced with simple friction drilling machining center. Friction drilling is not a material removal process and all drilled-hole material is transformed to form a bushing. Therefore, friction drilling process reduces waste of material. Moreover, friction drilled-hole connection is lighter than weld nuts or thread insert connection (Miller, 2006).

The main act in this process is friction leading to raising the temperature of process, increasing the material ductility and extruding onto the both sides of the drilled workpiece, respectively. In general, high heat generation changes the material properties and microstructural characteristics (Miller et al., 2006a; 2005). Moreover, friction increases erosion and wear dramatically. In other words, material degradation, erosion and wear have significant effects on quality and quantity of the process (Miller et al., 2007).

To generate heating and softening of material by frictional force, the spindle speed in friction drilling is higher than that in conventional drilling. To control material motion and bushing formation, the feed rate in friction drilling is lower than that in conventional drilling (Miller, 2006). Therefore, spindle speed and feed rate are two main quantity variables, which are known as process parameters, in friction drilling process (Streppel & Kals, 1983). Optimum spindle speed and feed rate lead to the sufficient heat generation that improves the bushing formation quality and reduces the tool wear (Ku et al., 2010).

Difficult-to-machine materials are referred to as the materials which generate extreme heating, subsequently produce excessive tool wear and poor process performance during the machining operation (Shokrani et al., 2012). The difficult-to-machine materials such as austenitic stainless steel AISI304, titanium alloy Ti-6Al-4V and nickel-based alloy Inconel718, having unique metallurgical properties, are widely applied in automotive, aerospace, nuclear and medical industries. However, they usually accompanies with low productivity, poor surface quality, and short tool life (Shokrani et al., 2012). The attractive advantages of austenitic stainless steel AISI304 are excellent corrosion resistance, high work-hardening rate, modest thermal conductivity, high temperature oxidation and good formability (Chow et al., 2008). Titanium-based alloys such as Ti-6Al-4V is readily regards as difficult-to-machine materials. It is often used in the aircraft industry due to the good compromise between mechanical resistance and tenacity, together with its low density and excellent corrosion resistance (Zhu et al., 2017). Nickel-based alloy Inconel718 is suitable to apply for high temperature conditions with creeping, corrosion and thermal shock resistance. Due to this, it may be often used in extreme environments such as aerospace and aircraft industry, gas turbine blades, seals and jet engine (Yang et al., 2012). Thus, the most significant issues that should be addressed in friction drilling of difficult-to-machine materials are friction drilling performance, product quality, and tool life.

1.1.1 Mechanism of Friction Drilling

Friction drilling involves five stages as shown in Figure 1.1. At the beginning, the drilling tool comes into the initial contact with the workpiece. The friction on contact surface, generating by axial force and angular velocity from drilling tool to workpiece, increases the temperature and softens the workpiece. The peak point of stress is also occurred in this step. At the second step, workpiece is softened, extruded, and pushed sideward and upward by drilling tool. Initial bulging in lower surface of workpiece, leading to the bushing formation, is also started in this step. At stage three, drilling tool enters to the softened workpiece and conical region is encompassed by melted and softened material. In sequence, drilling tool pierces the workpiece and bushing formation is begun. The peak point of temperature, which affects bushing formation, occurs in this step. At the fourth step, the drilling tool penetrates inside the workpiece more and pushes aside the workpiece-material. While the contact interface between tool and workpiece changes from conical to cylindrical region, bushing formation is completed. The process is finished when the drilling tool's shoulder pushes downward the softened back-extruded workpiece-material to form boss.

Meanwhile, the temperature reduces and distributes uniformly around the hole-wall. Finally, at the fifth stage, the drilling tool retracts and leaves the completed drilled-hole, while the temperature reduces gradually.

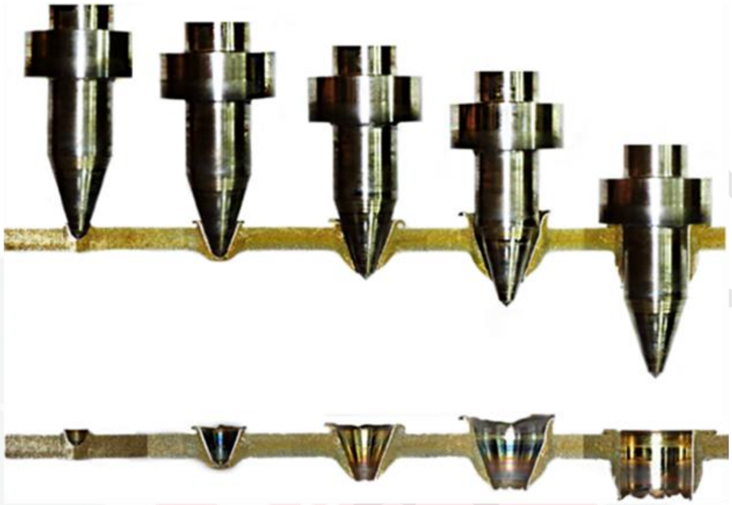

Figure 1.1: Stages in friction drilling process

1.1.2 Applications of Friction Drilling

Recently, a new method of friction drilling to join thin-walled flat profiles or multi-chamber hollow profiles have been presented (see Figure 1.2). In this method, friction drilling has been used to form a closed drilled-hole along the thickness of thin-walled profiles. Thin-walled structure has specific function in the lightweight construction. Moreover, using detachable joints in thin-walled structure can be seen as a unique advantage for lightweight construction (Biermann & Liu, 2014). Another method of friction drilling with approach to joining dissimilar materials have also been developed (see Figure 1.2). This method, calling flow drill screwdriving, is a one-sided thermo-mechanical joining process that has evolved from friction drilling. This process is able to form an bushing, thread-form the workpiece, and be tightened to provide a clamp load among the sheets (Urbikain et al., 2016; Skovron et al., 2015). As respect to the wide capabilities and unique advantages of friction drilling, which have been increased enormously in various industries, it is strongly believed that, this process can be applied on a broader scale of various fields. These include any plug connections in different fields such as automotive, aerospace, household appliance and other industries (Miller, 2006). Seat frame, exhaust system parts, fuel rail, seat handle, foot pedal and oxygen sensor are some examples of friction drilling applications in automotive industry. Moreover, friction drilling can be used to produce wheel frame of bicycle.

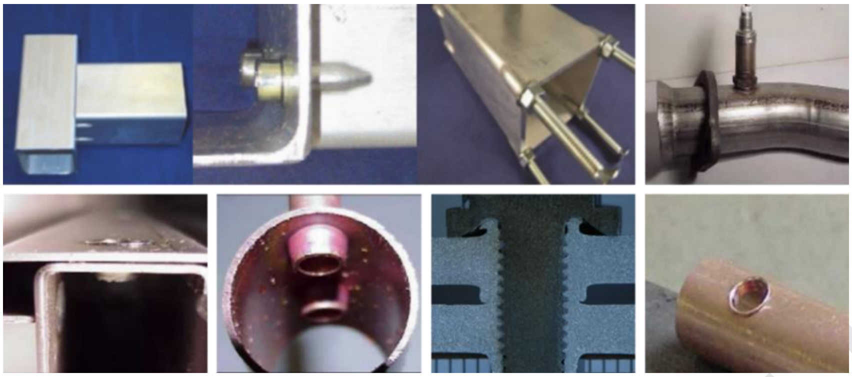

Figure 1.2: Example of applications of friction drilling

1.2 Problem Statement

Friction drilling is a non-traditional green hole-making process that is widely used in automotive and aerospace industries (Bilgin et al., 2015; Skovron et al., 2015; Biermann & Liu, 2014; Somasundaram et al., 2012). However, there is not any fundamental study to cover all aspects of this process. Although difficult-to-machine materials are applied in various fields of industry, especially aerospace and nuclear, less attention has been paid to friction drilling of them (Chow et al., 2008; Lee et al., 2007; Miller et al., 2005) and thus, more study is still needed. Insufficient friction drilling performance and excessive tool wear are the most important challenges and obstacles in friction drilling of difficult-to-machine materials (Lee et al., 2009, 2007; Miller et al., 2005). Hence, the improving of friction drilling performance and increasing the tool life are two critical issues that should be developed more. To improve friction drilling performance, a comprehensive study on correlation between associated physical processes of friction drilling and thermo-mechanical behaviors of the process parameters is necessary. The effect of these parameters on production quality and tool life are also required to study (Ozler & Dogru, 2013). Friction drilling increases thickness for threading and available clamp load, and simplifies joining process (Demir & Özek, 2014). Therefore, it has a wide range of applications in industry. On the other hand, difficult-to-machine materials are widely used in different fields of industries such as automotive, aerospace and medical (Sun et al., 2009; Baddoo, 2008; Henderson et al., 2004; Gurrappa, 2003). To improve the quality of hole-making for clamping and joining of difficult-to-machine materials, study on performance and analyzing effects of process parameters on performance are necessary.

Frictional heat generation leads to the softening material and subsequently forming the bush and degradation of the drilling tool. This highlights a deep study on temperature and thrust force of the process (Fernández et al., 2010). Meanwhile, investigation on effect of thermal properties of material and process parameters are crucial. Analyzing the experimentally measured temperature and thrust force help to better undestanding of frictional heat generation. The obtained results contribute to improve friction drilling performance and reduce tool wear by controling the heat generation and the thrust force in critical stages.

Tool wear is one of the noticeable parameters in all of the manufacturing processes (Lee et al., 2009; Miller et al., 2007). Since tool wear affects the characteristics and tolerances, which are achievable, it is a significant concern that must be received more attention (Miller et al., 2007). The excessive tool wear in friction drilling of difficult-to-machine materials more highlights the necessity of a fundamental study on tool condition and microstructural analysis of tool wear under different process parameters.

The finite element modelling is a powerfull tool to analyze complex problems like deformation, stress and temperature. It also has capable to show distribution of heat generation on workpiece-tool interface, softening of heated-up region and bushing formation, effectively. Moreover, simulation can prevent wasting material and time by replacement of experiments with simulation. However, the application of numerical analysis in friction drilling needs to be developed deeply (Miller & Shih, 2007). As tool condition is an important concern in friction drilling process, Miller (2006) recommended to extend finite element modelling for studying stress and temperature distribution in drilling tool during the friction drilling. Moreover, due to the main role of friction in this process, a study on frictional dissipation energy can help to better understanding of frictional heating generation effect on friction drilling performance. In general, there is not any consistent model for this process and no study has considered the effects of friction and heat generation on drilling tool. According to the issues and defects mentioned above, a fundamental study on friction drilling of difficult-to-machine materials is needed to conduct. In sequence, the issues need to be given a high consideration in this research to improve friction drilling performance and reduce tool wear are listed below:

1. Due to the lack of study on effects of process parameters on friction drilling performance and tool wear for difficult-to-machine materials, a study in this area may improve the productivity of process.

2. Frictional heat generation and thrust force, which have main act in friction drilling process, should be studied. The sufficient heat generation, which optimizes the thrust force, may help to improve the process performance and reduce the tool wear.

3. Since the insufficient or extreme heat generation has wrecking effect on product and tool life, microstructure of drilling tool and workpiece is important to analyze.

4. A better understanding of how frictional heat generation softens the material and forms the bushing may help to predict and control frictional heat generation during the process. Therefore, a finite element modelling is useful.

1.3 Research Objectives

The main aim of this thesis is identifying the effect of process parameters on drilling tool performance, bushing formation quality, thrust force and tool wear that contributes to improve friction drilling performance and reduce tool wear for friction drilling of difficult-to-machine materials. To achieve this aim, the present study's objectives are set out as follows.

1. To determine the friction drilling performance and analyze the response variables in friction drilling of the difficult-to-machine materials.

2. To measure and analyze the temperature and thrust force for better understanding of friction and heat generation.

3. To characterize the tool condition and microstructural change of workpiece by analyzing the wear, surface chemistry, and degradation of workpiece and drilling tool.

4. To develop a thermo-mechanical finite element model for analyzing the temperature and stress fields and also plastic deformation of the workpiece-material and drilling tool.

1.4 Significance of the Study

Friction drilling plays a key role in the future productivity of green manufacturing fields. From an enviromental point of view, it is well-known that ecological issues are taking relevance in the manufacturing industries.These industries represent 14% of the worldwide employment and it should be stated that it contributed in the USA economy with $2.25T in the last year (Pereira et al., 2019). On the other hand, from the technical point of view, the surface quality of friction drilled-hole is more appropriate and the formed bushing provides a perfect base for next production steps, such as threaing or joining processes. The significance of this work is to study friction drilling of difficult-to-machine materials, which has a wide range of applications in aircraft, medical equipments and automobiles, with approach to improve process performane and reduce tool wear. The friction drilling process, which increases the effectiveness of thread length and screw coupling for load clamping in joining application, can play significant role in various fields if performance and tool life are improved. Finite element modelling, as a strong tool for understanding the frictional heat generation on workpiece-tool interface, that helps to improve the friction drilling performance and control the tool condition during the process is developed deeply. It worth to mentioning that the effect of frictional heat generation on drilling tool has not been studied yet. In other words, since friction drilling is a thermal process with excessive mesh distortion and large deformation of the material, a more comprehensive and consistent thermo-mechanical model that includes sufficient damage criteria and advance meshing techniques is needed to study.

The findings of this study are expected to contribute for providing useful knowledge about mechanism of friction drilling of difficult-to-machine materials which have high resistance to corrosion and wear. They are also enhance the applicability of hole-making process in aerospace and medical industries, where difficult-to-machine materials are widely used.

1.5 Scope and Limitations of Research

The scope of this thesis focuses on experimental and numerical studies in friction drilling of difficult-to-machine materials. Experimental section is dedicated to a fundamental study on performance of friction drilling process, measurements of temperature and thrust force, and microstructural analysis of workpiece and drilling tool. In numerical analysis part of this study, finite element analysis of stress, strain and temperature of workpiece and drilling tool, which has not yet been fully analyzed in previous research works, is conducted.

1. This thesis is only limited on capability of computer numerical control (CNC) milling machine OKUMA MX-45VA for spindle speed and feed rate ranges.

2. The material used for drilling tool is tungsten carbide (WC), and austenitic stainless steel AISI304, titanium alloy Ti-6Al-4V and nickel-based alloy Inconel718 are for workpieces.

3. Since the design of drilling tool has direct relationship with frictional heat generation, material softening and bushing formation, the drilling tool is designed and fabricated based on the literature (Ku et al., 2011; Lee et al., 2009; Chow et al., 2008).

4. The process parameters are spindle speed and feed rate. The process parameters ranges are selected based on references and capability of CNC

machine. Moreover, the design of experiment (DOE) is carried out using full factorial method.

5. The drilling tool performance and tool wear for friction drilling were analyzed up to 20 drilling runs.

6. Since friction drilling is a dry machining process, experiments are conducted without cutting fluid.

7. According to heat generation during the friction drilling, which does not reach to melting point, and similar structural state of the heat affected zone (HAZ) to that of the base of material, which is caused by rapid cooling, heat affected zone (HAZ) is not covered in this study (Eliseev et al., 2017).

8. As the secondary process is required (i.e. threading) after friction drilling, the surface roughness is not measured.

9. To analyze tool wear, tool condition and microstructural changes of workpiece are characterized by scanning electron microscope (SEM) and energy dispersive spectrometry analysis (EDS).

10. Since friction drilling is not a material removal process and all material from drilled-hole is transformed to create a bushing, material removal rate is not considered.

11. The finite element modelling is developed using ABAQUS software. The stress, plastic strain and temperature distributions on workpiece and drilling tool are investigated.

1.6 Structure of Thesis

This thesis presents the research work on experimental and numerical analysis on friction drilling of difficult-to-machine materials, and it consists of five chapters. Contents of each chapters are briefly described as follows:

Chapter 1 presents an introduction to friction drilling, which contains background and motivation, basic mechanism, and process applications. Problem statement, objectives and scope of thesis are also stated in this chapter.

Previous works on friction drilling and related topics are reviewed in Chapter 2. This chapter also includes different drilling processes and difficult-to-machine materials. Since wear, which is caused by interaction between drilling tool and workpiece, is significant concern in friction drilling process, different mechanisms of tool wear are also reviewed. In addition, basic information and governing equations related to finite element modelling are presented.

In Chapter 3, the equipment and methods using in experimental work and numerical analysis are described. This chapter starts with explanation of main equipments used in experimental work. In sequence, a geometrical model for drilling tool is designed. The properties of workpiece and drilling tool are also considered. In section of experimental work, the measurement methods of bushing height, hardness, roundness, temperature, thrust force, and microstructure are presented. Model development and simulation of friction drilling are presented in the section of finite element method.

The experimental and numerical results are discussed in Chapter 4. Experimental results section covers friction drilling performance, temperature, thrust force and microstructural alteration. The second section is started with validation of numerical results with experimental results. Then, stress, strain and temperature distribution on workpiece and drilling tool are discussed.

Chapter 5 is dedicated to present conclusion of this research work. The main contribution of this thesis to the friction drilling of difficult-to-machine materials and some recommendations for future works are given in this chapter.

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LIST OF PUBLICATIONS

Journal Publication

Shayan Dehghan, Mohd Idris Shah Ismail, Mohd Khairol Anuar Mohd Ariffin and B.T Hang Tuah Baharudin. Experimental investigation on friction drilling of titanium alloy, Engineering Solid Mechanics, vol. 6, no. 2, pp. 135-142, 2018.

Shayan Dehghan, Mohd Idris Shah Ismail, Mohd Khairol Anuar Mohd Ariffin and B.T Hang Tuah Baharudin. Experimental investigation on friction drilling of stainless steel AISI 304, International Journal of Machining and Machinability of Materials, Accepted.

In Preparation

Shayan Dehghan, Mohd Idris Shah Ismail, Mohd Khairol Anuar Mohd Ariffin and B.T Hang Tuah Baharudin. Experimental investigation on friction drilling performance in friction drilling of austenitic stainless steel AISI304.

Shayan Dehghan, Mohd Idris Shah Ismail, Mohd Khairol Anuar Mohd Ariffin and B.T Hang Tuah Baharudin. Experimental investigation on friction drilling performance in friction drilling of titanium alloy Ti-6Al-4V.

Shayan Dehghan, Mohd Idris Shah Ismail, Mohd Khairol Anuar Mohd Ariffin and B.T Hang Tuah Baharudin. Experimental investigation on friction drilling performance in friction drilling of nickel-based alloy Inconel718.

Shayan Dehghan, Mohd Idris Shah Ismail, Mohd Khairol Anuar Mohd Ariffin and B.T Hang Tuah Baharudin. Investigation on temperature and thrust force in friction drilling of AISI304, Ti-6Al-4V and Inconel718.

Shayan Dehghan, Mohd Idris Shah Ismail, Mohd Khairol Anuar Mohd Ariffin and B.T Hang Tuah Baharudin. Microstructural study on friction drilling of difficult-to-machine materials with approach to wear mechanisms identification and improve friction drilling performance.

Shayan Dehghan, Mohd Idris Shah Ismail, Mohd Khairol Anuar Mohd Ariffin and B.T Hang Tuah Baharudin. Numerical analysis of drilling tool and tool wear in friction drilling.

Shayan Dehghan, Mohd Idris Shah Ismail, Mohd Khairol Anuar Mohd Ariffin and B.T Hang Tuah Baharudin. Advanced finite element analysis for friction drilling process of difficult-to-machine materials.

Conference Presentation

Shayan Dehghan, Mohd Idris Shah Ismail, Mohd Khairol Anuar Mohd Ariffin and B.T Hang Tuah Baharudin. Numerical simulation on friction drilling of aluminum alloy, 2nd International Conference on Mechanical, Manufacturing and Power Plant Engineering (ICMMPE 2016), No.169854 – Kuala Lumpur, Malaysia, 2016.

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