INFLUENCE OF PROCESS PARAMETERS IN FRICTION DRILLING OF TITANIUM TI-6AL-4V ALLOY

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Friction drilling is a process of using the friction between the rotating conical tool and the workpiece to generate heat and deform the work piece's material and penetrate the hole. The softened material is pushed sideward and downward to make the bushing. This paper aimed to study the influence of friction drilling parameters. Thrust forces and torque forces were analysed. Experiments were carried out with a friction drill tool made of tungsten carbide on titanium grade Ti-6Al-4V. The parameters used in this study were spindle speed and feed rate. It was found that the thrust force and torque decreased with increased spindle speed and with decrease of feed parameters. The microstructure reveals that deformed grains at hole's surface relate to hardness on the cross-section of workpiece. The highest value of microhardness was 813.2 HV and reduced to the original hardness of the matrix material.

KEYWORDS

Friction drilling, Titanium Ti-6Al-4V, Thrust force, Torque force, Hardness

1 INTRODUCTION

Friction drilling (Flow drilling or Thermal drilling) is a modern, innovative, and non-chip drilling technique for making holes in a metal sheet [Szwałek 2018]. This technique is substantially different from the current method in which metal is penetrated by shear force. With friction drilling, the heat generated between a rotating conical tool and a workpiece is used instead of shear force to drill a hole [Kaya 2014]. A conical tool can penetrate through a metal sheet when the temperature between the two surfaces is high enough. At such a temperature, a metal sheet in a solid-state is transformed into a semi-liquid state, which is soft enough for making a hole.

Generally, making a hole with other methods can cause many drawbacks such as hard to join with other parts, not enough hole surface to create threads, etc. Theoretically, these drawbacks can be overcome by friction drilling methods. There are many advantages of using friction drilling compared to other methods, i.e., high-quality bush, hole and ring, joints are more durable, no need for individual machines such as welding machine, etc., high load capacity of bearing bushes, suitable for automated manufacturing processes, less material and lower weight due to the use of thin profiles; it is possible to produce bushes in blind sections because there is no need for support at the rear, the processing time is reduced and, additionally, production capacity is increased, no cutting fluid or lubricant is necessary and, lastly, waste of material is reduced [El-Bahloul 2013,Szwałek 2018].

Titanium (Ti-6Al-4v), which is an alpha-beta titanium alloy has a high strength-to-weight ratio, high resistance to chemical, industrial and natural corrosion, high resistivity, and high creep resistance property. Therefore, this material is a Titanium alloy that is widely used in many industries, e.g., racing industry, aerospace industry, marine application, biomechanical application, chemical industry, and gas turbines [Zhang 2008]. Importantly, Titanium (Ti-6AL-4v) has a low thermal distribution, which is appropriate for the friction drilling process because generated heat is restricted to only a specified point. However, research in the area of friction drilling with Titanium (Ti-6Al-4V) has received little attention until now [Boopathi 2017, Demir 2013, Li 2001].

The objective of this research is divided into two issues. The first issue is to explore a relationship between thrust and torque force with the friction drilling parameters. The second issue is to investigate a characteristic of the drilled surface hardness with selected drilling parameters.

Friction drill theory and related researches are presented in section 2. In section 3, the details of the experiment are shown. An analysis of the results is expressed in section 4. Finally, conclusions are drawn in section 5.

2 THEORY AND LITERATURE REVIEWS

2.1 FRICTION DRILLING THEORY

Friction drilling, also known as 'thermal drilling,' 'flow drilling,' 'form drilling,' or 'friction stir drilling', is a metal drilling process without a shear force. This drilling method utilizes the heat generated from friction, which occurs between a rotating conical tool and a metal plate [Kaya 2014]. At a specified temperature, metal at a target point is to softened enough to make a hole. This process is chip free and clean, which means all removed metal becomes a bush and ring in situ. In theory, a bush thickness should be three times that of a workpiece thickness. Additionally, the formed bush and ring allow a tight connection without the use of additional connecting elements, such as nitrile threads [Szwałek 2018].

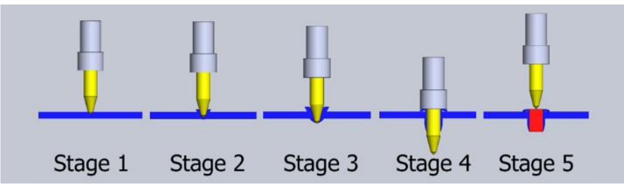

Figure 1. Stages in friction drilling process

A friction drilling process is comprised of 5 stages, as shown in Figure 1. In stage 1, the tip of the conical tool contacts a workpiece at a target point. The heat generated from friction between the tool and workpiece will soften the workpiece. In stage 2, the drilling tool continuously penetrates into the workpiece. The thrust force is typically at its maximum, and the back extrusion of metal can be observed. In this stage, the work-material is initially pushed sideward and upward. In stage 3, the friction drill penetrates into the workpiece. This is the friction drill location where the maximum torque is observed [Kaya 2014]. The tool moves forward to form a bush and ring in stage 4. Furthermore, as the process is completed, the shoulder of the tool may contact the workpiece to collar the back extruded burr on the bush [El-Bahloul 2013]. Finally, in stage 5, the tool is quickly withdrawn from the drilled hole.

2.2 LITERATURE REVIEWS

In friction drilling, there are two important parameters, i.e., rotational speed and feed rate. Rotational speed or speed of revolution is a speed of object around an axis represented in the form of the number of turns of the object divided by time. Feed rate is the relative velocity at which the cutter is advanced along or into the workpiece; its vector is perpendicular to the vector of cutting speed. These two parameters have significant effects on the surface roughness of the workpiece [Aslan 2018]. It is very important to use the appropriate parameters that lead to the correct temperature for creating a hole without any defects. When the correct temperature is not reached, friction is not smooth over the drilled area, and this results in chip adhering on the tool surface, which damages the hole surface and increases surface roughness [Chow 2018].

Nowadays, Titanium Alloy is a popular high-value material that is widely used in many industries. It has a precious mechanical property that is very appropriate for industrial usage, e.g., high strength per weight ratio, high corrosion resistance both in natural and industrial environments, high creep resistance and high resistivity. Obviously, friction drilling, which is a chip free method, is very suitable for drilling this material. Generally, two major aspects should be considered in using friction drilling on Titanium Alloy material. Firstly, because Titanium Alloy is very strong material, drilling with friction drilling usually generates a large amount of axial and torque force and can result in high damage to the drilling machine. Hence, a study that explores a relationship between these two forces and a set of drilling parameters is required. Another important aspect is a relationship between drilling parameters and shapes of the bush and ring. The shape of bush and ring must conform to the purpose of usage.

Compared a number of holes that could be created by coated drill head and uncoated drill head. The research showed that the uncoated drill head could be used for 5,000 – 15,000 holes whereas the coated drill head could be used for between 100,000 – 160,000 holes[Kerkhofs 1994]. A paper by [Pantawane 2011] investigated the effect of friction drilling input parameters of rotational speed, feed rate and tool diameter on the responses, i.e. dimensional error and surface roughness of the bush. Moreover, they also studied the pattern of wear of the Tungsten carbide tool which was used to penetrate a steel sheet (AISI 1015). They concluded that tool wear can help reduce shear force significantly. [Kaya 2014] investigated the effects of drilling parameters on surface temperature, thrust and torque force in friction drilling of ST12 material. The experiment showed that the thrust and torque force gradually increased with increasing friction angle, feed rate and Friction contact area ratio.

On the other hand, the thrust and torque force decrease with increasing drilling speed. In [Nama 2016], the effect of process conditions and pre-drill diameter on temperature, drilling force, bush height, and bush thickness of A6063-T6 aluminium alloy were studied. It was concluded that a pre-hole helps in obtaining uniform bush thickness and reduces the heat and force to perform the process.

Up to now, there are few pieces of research in the area of friction drilling of Titanium material. In [Miller 2006], friction drilling on many types of metal sheets was tested, e.g., AISI 1020 steel, AISI 4130 steel, Al 5052, and Titanium. It was found that friction drilling of a Titanium plate was the hardest. In addition, the effects of pre-heating and high-speed friction drilling were studied on two other materials, i.e., cast Al and Mg alloys. The results showed that shear and torque force were decreased, and the bush shape was Improved when temperature was increased [Miller 2006]. An investigation on effects of spindle speed and feed rate on bush height, shape, and hardness in friction drilling of titanium alloy Ti-6Al-4V showed that 1500 rpm rotational speed, and feed rate 65 mm/min have significant influences for achieving better bush shape and height, prolong tool life, and lower hardness [Dehghan 2018].

3 EXPERIMENTAL

3.1 EXPERIMENTAL PROCEDURE

In this experiment, the work material was Titanium alloy Ti-6Al-4V with the dimension of 100×40×2.5 mm. Drilled holes on each plate had a diameter of 5.3 mm. The chemical composition and mechanical properties of Titanium alloy Ti-6Al-4V are shown in tables 1 and 2, respectively. The friction drill tools were fabricated from tungsten carbide K20 with hardness 81.5 HRC.

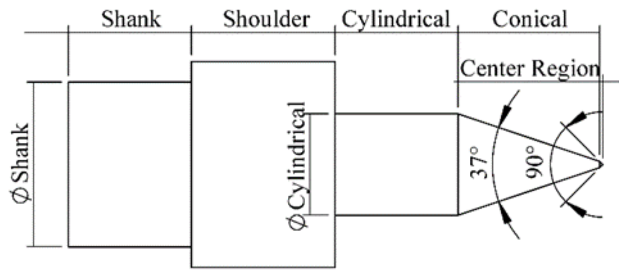

Figure 2. Details of the friction drill tool

Figure 2 shows the details of the friction drill used in this research. Shank, shoulder, cylindrical, conical, and centre regions were 13 mm., 7 mm., 10 mm., 6 mm. and 1 mm., respectively. Moreover, shank, shoulder and cylindrical diameters were 8 mm , 10 mm, and 5.3 mm whereas the centre and conical angles were 90□ and 37 degrees. The spindle speed and feed rate were set as shown in table 3.

composition	Ti	Al	V	Fe
Ti-6Al-4V	Base	5.5-6.75	3.5-4.5	< 0.25

Table 1. Chemical compositions of the workpiece

Ti-6Al-4V Mechanical properties	
Hardness (HV)	393
Tensile strength (Ultimate) (MPa)	950
Tensile strength (Yield) (MPa)	880
Modulus of Elasticity (GPa)	113.8
Compressive Yield Strength (MPa)	950
Poisson’s ratio	0.342

Table 2. Mechanical properties of the experimental plate

Parameters	
Feed rate (mm per minute)	80,100,120
Spindle speed (rpm)	2,500 3,500 4,500 6,000 7,000

Table 3. The drilling parameters’ settings

3.2 EXPERIMENTAL SETUP

3.2.1 THRUST AND TORQUE FORCE MEASUREMENT

This experiment was conducted on CNC vertical machining center Eumach Model LMC 1020. The thrust and torque forces were measured by Kistler 9255B dynamometer as shown in Figure 3. Furthermore, a microscope was used to inspect the shape of the ring and bush.

Figure 3. Friction drill process setup

3.2.2 HOLE SURFACE HARDNESS MEASUREMENT

The cross-sectional hardness of the specimen, which had been cut off after drilling, was measured using the Vickers hardness test. The 100g load was applied up to 5 seconds. There were ten indentations in two directions: X-axis and Y-axis. The spacing between the indentations was 0.1 and 0.5 mm, respectively, and the average of three readings in each specimen was taken, as shown in Figure 4.

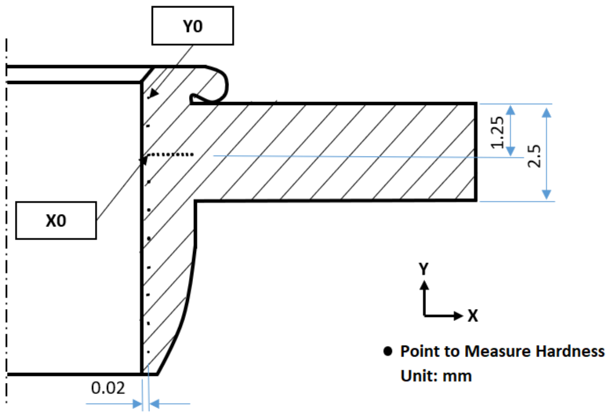

Figure 4. Hole surface hardness measurement set up

4 ANALYSIS OF THE RESULTS

4.1 THRUST AND TORQUE FORCE ANALYSIS

Figure 6 shows the relationship between torque force and spindle speed at various feed rates. It can be observed that drilling torque values decreased with increase of spindle speed from 2,500 to 4,500 rpm. On the other hand, drilling torque values increased when spindle speed was increased from 4,500 to 7,500 rpm. It can be seen that torque force was relatively low at 4,500 rpm due to heat generated between the drilling tool and the working material. This heat made the titanium alloy surface soft enough to be penetrated resulting in a considerably low torque force. This occurrence corresponds with a result found by Miller [Miller 2006]. However, at spindle speeds of 4,500 - 7,000 rpm, the heat generated between the two surfaces will not only soften the titanium plate but also destroy a drilling tool as shown in Figure 5 (b) and result in an increase of torque force as can be seen in Figure 6.

Moreover, when feed rate was increased, the torque force was slightly higher. The explanation is that when feed rate is increased, the drilling tool will move forward to penetrate the titanium alloy workpiece rapidly, limiting time for heat generation. In contrast, at lower feed rate, the drilling tool takes a longer time to complete the process, thus allowing more heat to be generated. Hence, this lower feed rate reduces flow stress of a workpiece. The results are similar to those reported by [Kuan-Yu 2018]. Moreover, it can be observed that the minimum torque force was obtained when the spindle speed and feed rate were 4500 rpm and 80 mm/min respectively.

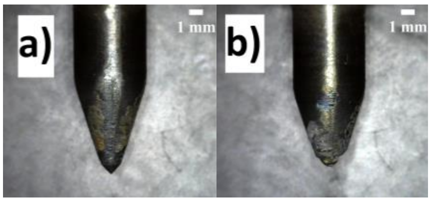

Figure 5. Comparison friction drills tool after the process at a)4500 rpm and b)7000 rpm

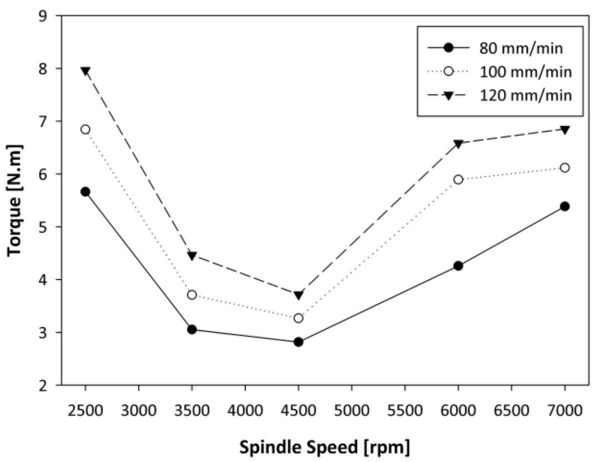

Figure 6. Relationship between torque force and spindle speeds at various feed rates

Figure 7 depicts the effects of feed rate and spindle speed on thrust force while drilling the Titanium alloy Ti-6Al-4V plate. It can be seen that thrust force increased when feed rate was increased, whereas it decreased when spindle speed was increased [Krasauskas 2011]. This phenomenon can be explained by higher spindle speed causing high temperature between the two surfaces [Dehghan 2018, Demir 2012, Miller 2005]. With this high temperature, the drilling tool could penetrate through the workpiece with a low thrust force as shown in Figure 7. It shows that regardless of spindle speed, decreasing feed rate would reduce thrust force, resulting in less compression between the drilling tool and the working material.

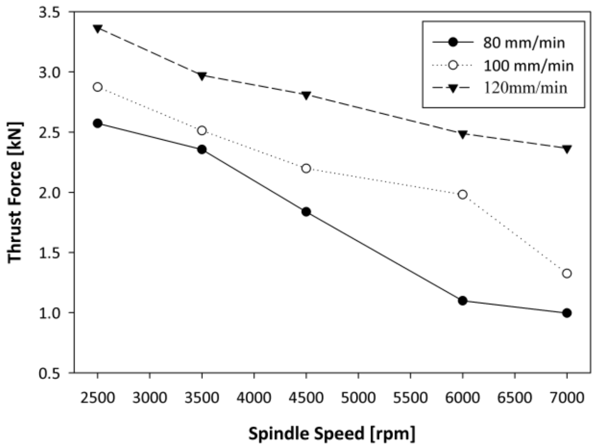

Figure 7. Relationship between thrust force and spindle speeds at various feed rates

4.2 THE DRILLED HOLE SHAPE ANALYSIS

Figures 8 and 9 represent the bush and ring shapes of the drilled holes. They are analyzed by thrust, torque forces and two parameters: spindle speed and feed rate. Figure 8 shows the drilled hole that occurred with the least thrust force had a torn ring, a short bush and a metal blister in the mouth of the hole. Figure 9 shows the shape of the drilled hole with the least torque force. It had the best appearance for ring and bush from drilling at 4500 rpm and 80 mm/min feed rate. With these drilling parameters, thrust and torque forces were 1.3 kN. and 5.8 N.m., respectively. It can be concluded that this set of drilling parameters resulted in the least thrust and torque force and also affected the characteristics of the drilled holes.

Regarding spindle speed parameter, 4500 rpm spindle speed with 80 mm/min feed rate seemed to generate the appropriate heat between the two surfaces to make the titanium plate soften enough to be penetrated without causing damage to the tool. It correlates with Figure 7(a). The softened material could easily flow along the drilling tool. Furthermore, this softened material flowed upward and downward to create a bush and ring efficiently. But at 7000 rpm and 80 mm/min feed rate, the drilling bit and hole surface moved against each other for a relatively long time which caused overheat at the hole surface. With this phenomenon, the working material would remain in a liquid state. As a result, a large amount of liquid material flowed along the drilling bit and created an incompatible bush and ring, as can be seen in Figure 8

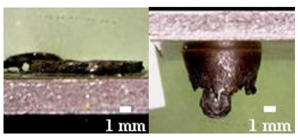

Figure 8. Hole with feed rate 80 mm/min and 7000 rpm

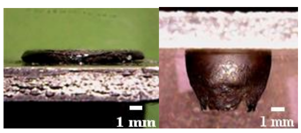

Figure 9. Hole with feed rate 80 mm/min and 4500 rpm

4.3 HARDNESS OF CROSS SECTIONS OF FRICTION-DRILLED HOLES : TEST RESULTS

Figure 10 shows microhardness profiles on the cross-section along the X-axis. It was found that the point of highest hardness was at a distance of 0.02 mm from the hole surface or 0.00 on X-axis; it was the first point measured along the X-axis, and the hardness was higher than the normal hardness of the material. With increasing distance from the surface, the hardness reduced to the original hardness of the matrix material. This indicated that in the area where the material was in direct contact with the tool, frictional heat caused the drill hole surface to increase its hardness. The explanation is that hardness increased at the hole surface due to thermo-mechanically affected zone (TMAZ) and recrystallization, as shown in Figure 12 and Figure 13. [Boopathi 2017, Eliseev 2017]. The highest value of microhardness was 813.2 HV.

Figure 11 presents microhardness values on the Y-axis., the microhardness Ti-6Al-4V increased significantly at a depth of 2.0 mm because of work hardening in terms of grain-flow in the dislocation density.

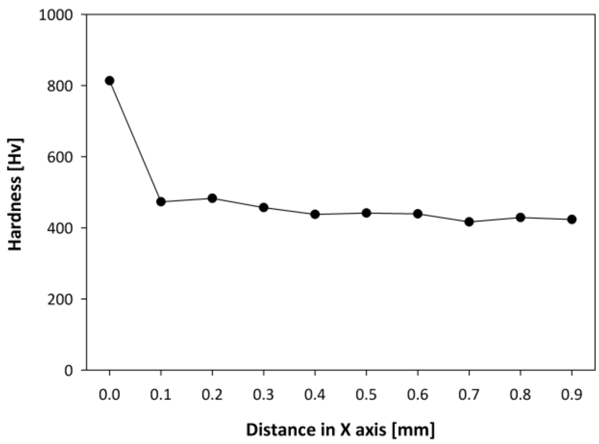

Figure 10. Micro hardness profiles on the cross section along X-axis

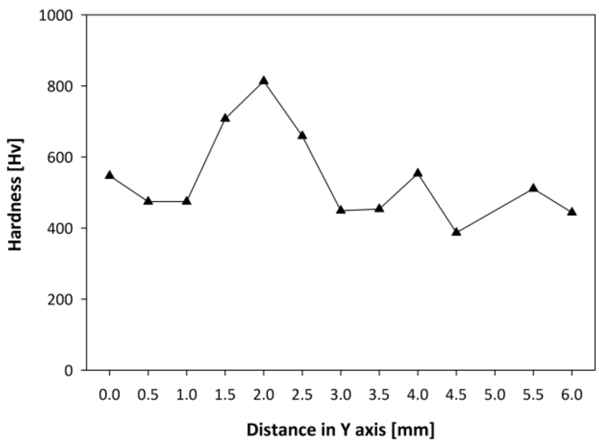

Figure 11. Micro hardness profiles on the cross section along Y-axis

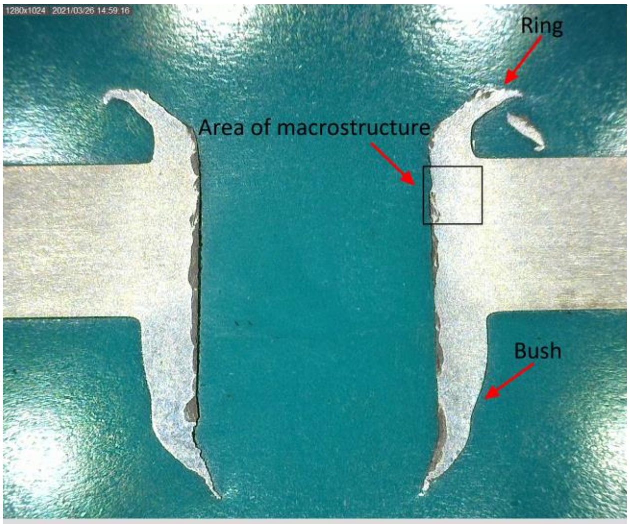

Figure 12. Area of Macrostructure of cross section of friction drilled hole

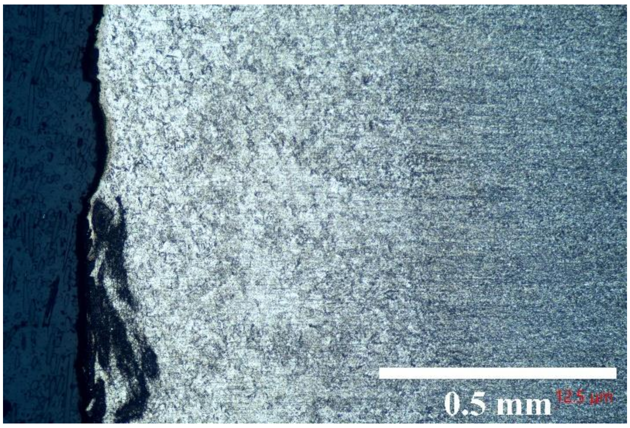

Figure 13. Macrostructure of cross section of friction drilled hole pattern of titanium alloy Ti-6Al-4V plate after drilling process

5 CONCLUSIONS

Friction drilling is a non-chip method that can be used for drilling high-value material such as titanium alloy. It is concluded that drilling with 4500 rpm spindle speed gave the lowest torque force, which increased with spindle speeds up to 7000 rpm. Spindle speed of 4500 rpm and 80 mm / min feed rate gave the lowest torque and thrust force compared to feed rates of 100 mm/min and 120 mm / min. Spindle speed 4500 rpm and Feed rate 80 mm/min produced a good bush shape that correlated with torque and thrust force. When feed rate was increased from 80 mm/min to 100 mm/min and 120 mm/min, torque force increased because the time to heat the workpiece sufficiently was not enough. In addition, hardness in the Y-axis also gradually increased a little.

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