Experimental Study of the Effect of Rotational Speed, Feed Rate, Lubricant and Tool Material in Friction Drilling of the Titanium Sheets

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Abstract
In this research, the effects of the rotational speed, feed rate, tool material and lubricants on the tool life and the hole quality are studied in the frictional drilling of the titanium sheets. The friction drilling tests are performed on a CNC milling machine. Furthermore, 5 specimens are selected and their metallurgical structures are studied. The results show thatamong the input parameters, the rotational speed and feed rate significantly alter the output parameters.Furthermore,the results showed that the best hole quality can be achieved using a WC tool material along with appropriate lubricant. The tool geometry is also an important factor that can excel the produced hole quality and increase the tool life. The metallurgical results also showed that because of the severe plastic deformation of the layers close to the hole surface, the hardness of these layers is higher than that of the other regions in the workpiece.

Keywords
Friction Welding, Titanium Sheets, Speed, Feedrate, Lubricant, Tool Material, Thermal Conductivity

1. Introduction
Friction drilling is a new drilling method for drilling of the thin sheets. The method employs the heat resulted from the friction between a conical drilling tool and the sheet surface, resulting in the production of a chipless bushing-shaped hole in the sheet. The method is therefore environmentally cleaner than conventional drilling, as it produces no chip to discard [1].

The friction drilling tool is a rimmed conical-shaped tool. When the tool is rotated at high speed and pressed firmly against the sheet, the generated heat softens the sheet, which enables the tool to be penetrated into the sheet. In this step, a hole is generated in the sheet and the excessive material forms a bushing-shaped wall around the hole [1, 2]. The process is schematically illustrated in Figure 1.

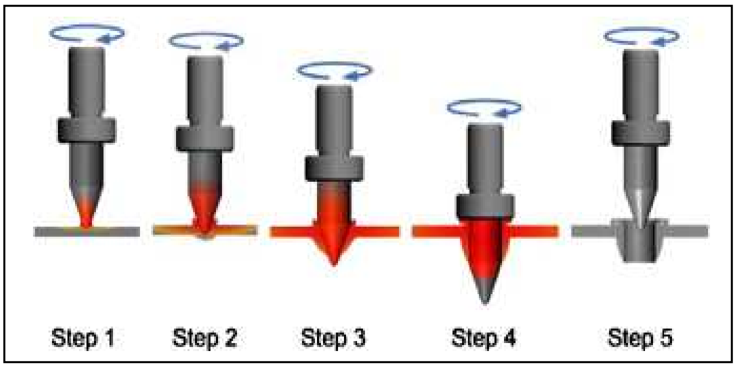


Figure1. The friction drilling method [3]

There are some relevant research works available in the literature. Chow et al. have studied the frictional drilling of steel AISI 304 [3]. They have studied the optimum drilling parameters and tool geometry. Urbain et al. have combined friction drilling and form tapping for joining aluminum and steel [4]. Demir and Özek have investigated the effect of pre-drilling on the bushing shape of A7075-T651 [5]. Mutalib et al. have conducted their research toward the investigation on the tool wear in friction drilling and studied the different wear mechanisms in friction drilling [6].

As can be found from the literature, no research work has clearly addressed the friction drilling of the titanium alloys and the problems emerge while friction drilling of such a hard-to-drill material. In this research, the friction drilling process is performed on the 3 millimeters thick pure titanium sheets which are used in underwater structures due to their high corrosion resistance [7]. The effects of the rotational speed, feed rate, lubricant and tool material are studied on the hole quality and tool life experimentally. In the experimental tests, universal and CNC milling machineis employed in order to study the effect of different speed and feed rate. Two tool materials (i.e. WC and hot working steel) are evaluated and compared. The use of the lubricant is also studied. The results are reported in terms of the hole quality, surface roughness and the metallurgical structure of the holes.

2. Materials and Equipment

The sheet metal which is used is non-alloyed titanium with %99 purity. The chemical composition of the sheet is presented in Table 1.

Table1. The chemical composition of the sheet metal

Composition	C	Fe	H	N	O	Ti
Wt%	1-0 Max	0.3-0 Max	0.015-0 Max	0.03-0 Max	0.25-0 Max	99-5.99

The tool is also illustrated in Figure 2. The dimensions are presented in Table 2.

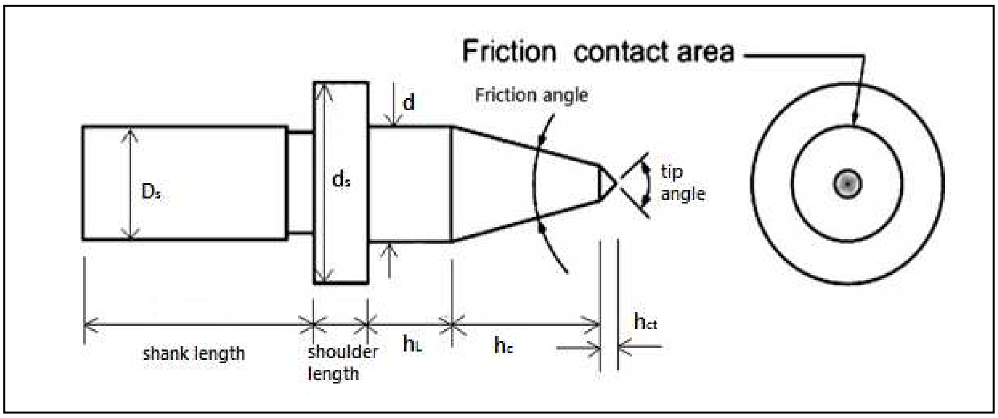


Figure2. The friction drilling tool

Table2. Dimensional parameters of the tool

The dimension	amount	The dimension	amount
Central area length (h_{ct})	1 mm	The diameter of the cylindrical zone (d)	
Conical zone length (h_c)	3.5 mm	The diameter of the rimmed zone (d_s)	
Cylindrical zone length (h_L)	7.5 mm	The diameter of the stem (D)	
Length of the rimmed zone	7 mm	Tip angle (α)	
Length of the stem zone	12 mm	Friction angle (β)	
Frictional surface contact rate	%100		

The lubricant which is employed in this research is the FDKS oil from FLOW DRILL Company.

2.1 The Test Setup

A CNC milling machine is employed for the friction drilling process. The tests are performed in two phases: with constant and variable feed rates. The constant feed rates are presented in Table 3 along with the spindle speeds, while the variable feed rates are presented in Table 4.

Table3. The constant feed rates

Spindle speed (rpm)	800	1000	1300	1600		
Feed rate (mm/min)	40	80	120	160	200	240

All of the constant-feed-rate tests are performed with two tool materials (i.e. steel 1.2344and CW). The total number of tests is 26. An infrared thermometer is employed to measure the temperature of the tool-workpiece contact zone. The tool-workpiece temperature at the beginning of the process is between 700 to 900˚C.

The amount of feed rate changes is selected in accordance with the titanium heat transfer characteristics, tool geometry and the workpiece thickness.

Table4. Spindle speeds and feed rates in variable feed rate tests

Spindle speed (rpm)	Feed rates					
1000	80	100	120	140	160	200
1300	100	120	140	160	200	240

The variable feed rates are achieved by writing and entering an NC code into a CNC machine. The increasing trend of the feed rate is illustrated in Figures 3 and 4 for two spindle speeds.

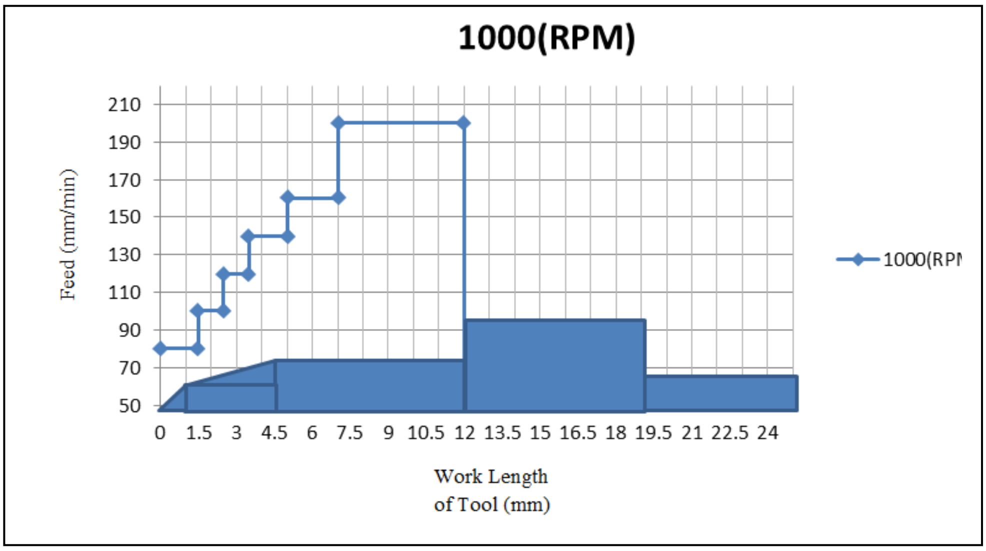


Figure3. The variable feed rate for spindle speed 1000 rpm

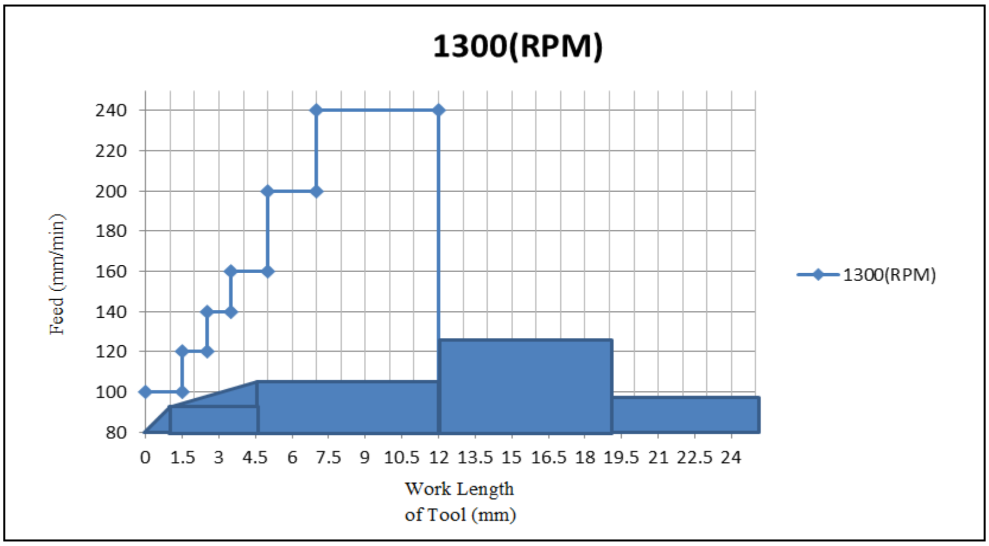


Figure4. The variable feed rate for spindle speed 1300 rpm

In this method, the tool is fed to the sheet with a constant feed rate to produce heat with the depth more than the length of the central area and then is changed stepwise. After the production of the samples, 5 samples are selected which have the best quality in terms of appearance, bush length, completeness of the hole and the amount of the built-up edge. The samples are numbered according to Table 5.

Table5. The selected samples' characteristics

Sample	Spindle speed (rpm)	Feed rate (mm/min)	The machine	Bush length (mm)
A	1000	Stepwise feed rate	CNC machine	5.8
B	1300	80	Universal milling machine	6.4
C	1600	160	Universal milling machine	8.3
D	1600	200	Universal milling machine	8.1
E	1000	120	Universal milling machine	8

2.2 The Tool Life

The tool life is studied after 20 holes production trials via stereo microscope, in terms of the built-up edge and the tool wear. The results are illustrated in Figure 5.

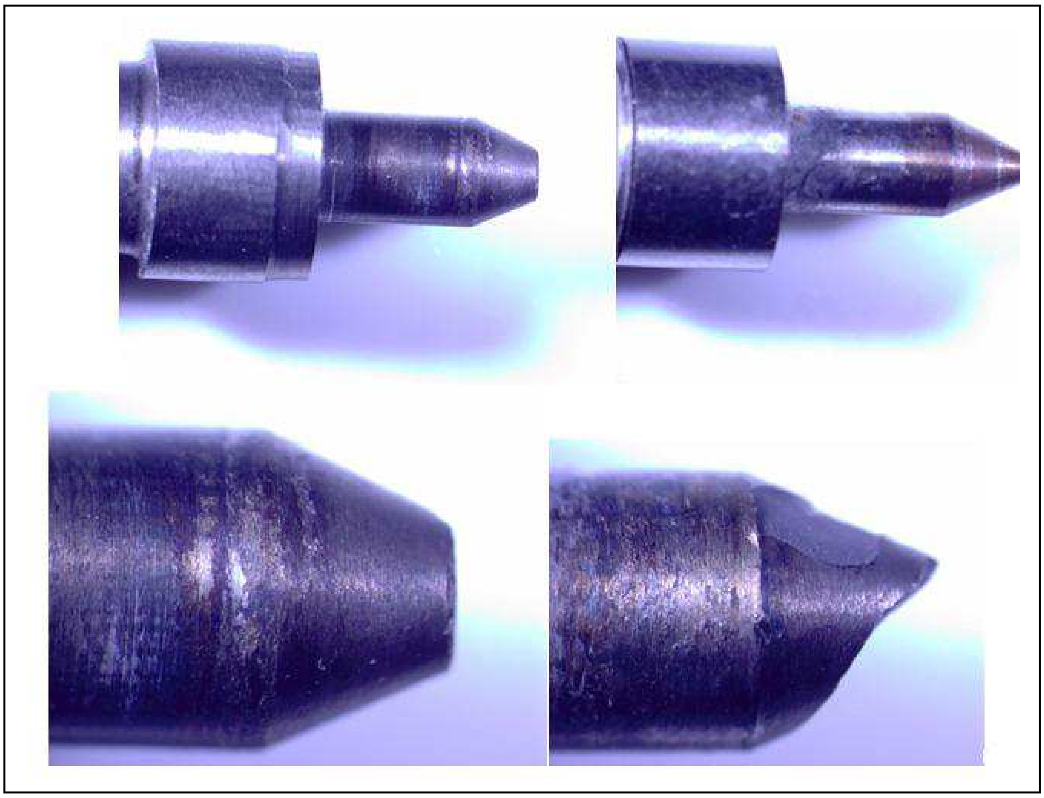


Figure5. Tool wear results

2.3 Surface Roughness

The cross-sections of the samples are prepared for roughness measurement after frictional drilling. The results of the surface roughness are presented in Table 6.

Table6. The surface roughness results

Sample	R_a	R_z
A	14.09	73.6
B	1.25	9.24
C	0.351	3.69
D	3.842	30
E	0.342	3.51

2.4 The Topography of the Samples

The topographies of the internal surfaces of the produced holes are studied by a stereo microscope, which is presented in Figure 6.

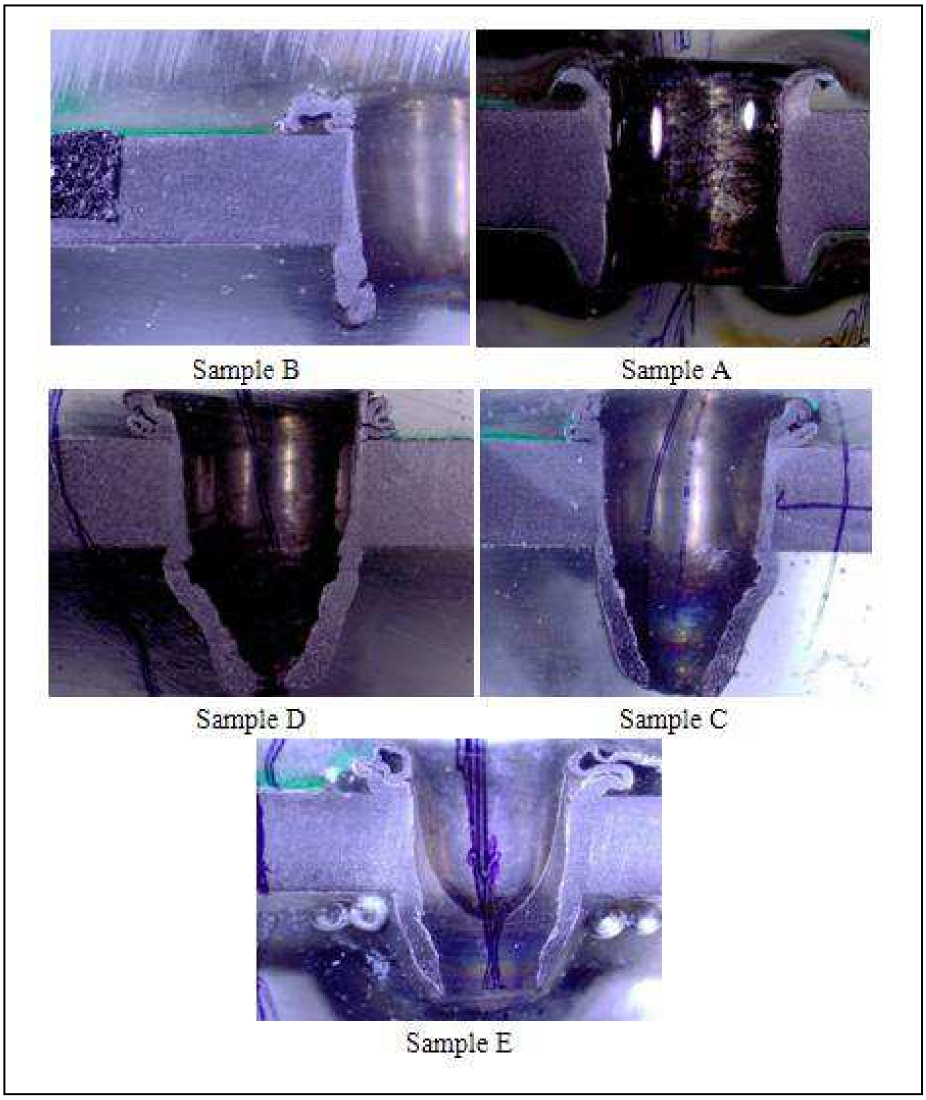


Figure6. The topography of the produced holes

2.5 Preparation of the Surfaces and Metallography

The samples' cross-sections are polished primarily and then etched in the following combination of the etchants [8, 9]:

3ml HF + 3ml HNO_3 + 100ml H_2O

The surfaces are then studied with an SEM. The results are presented in Figure7.

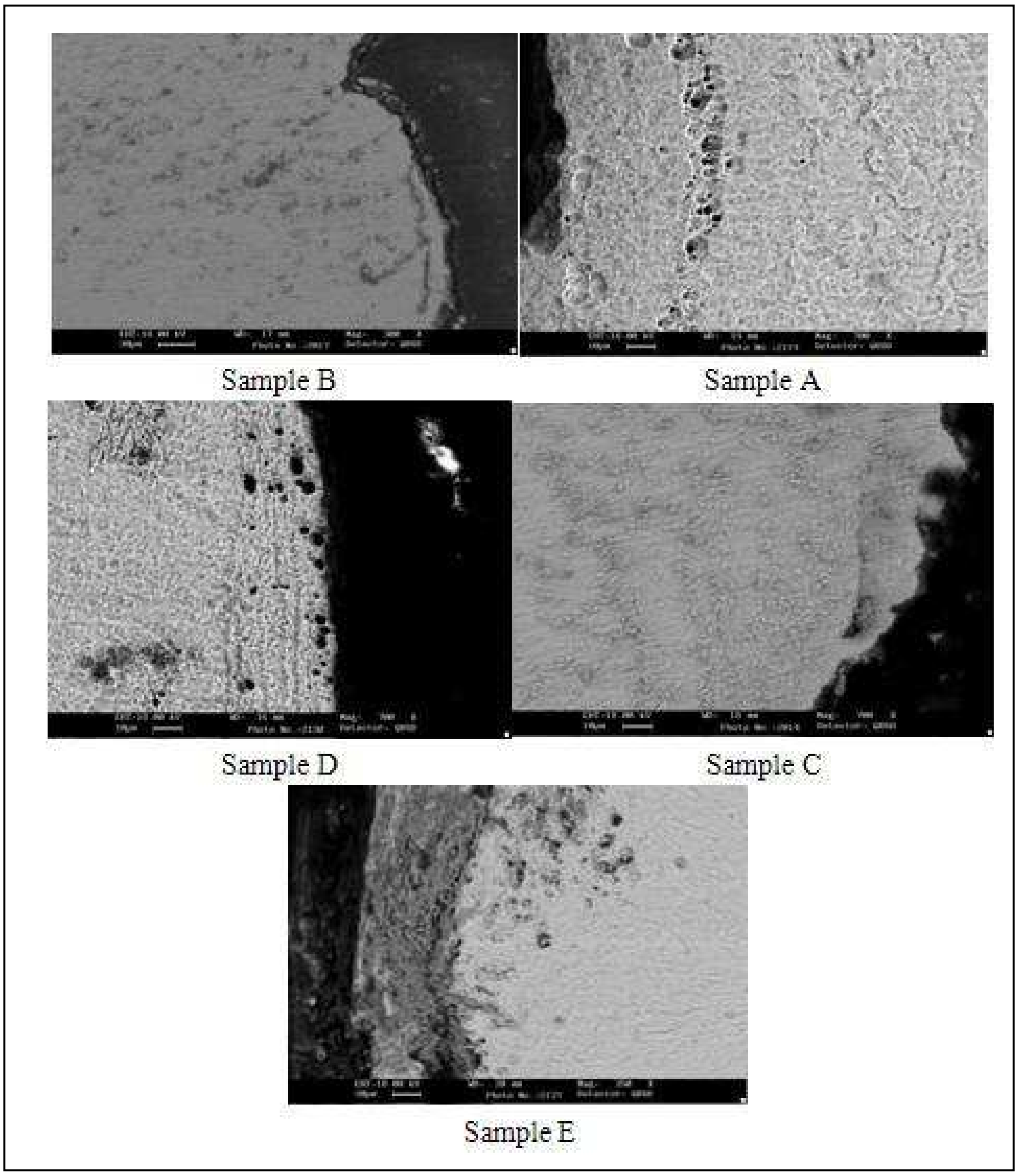
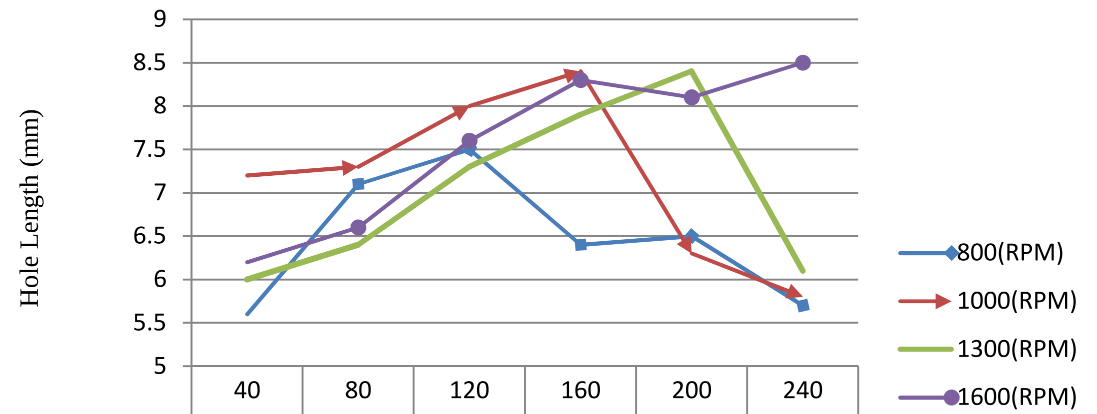


Figure7. The SEM picture of the hole section

3. Results and Discussion

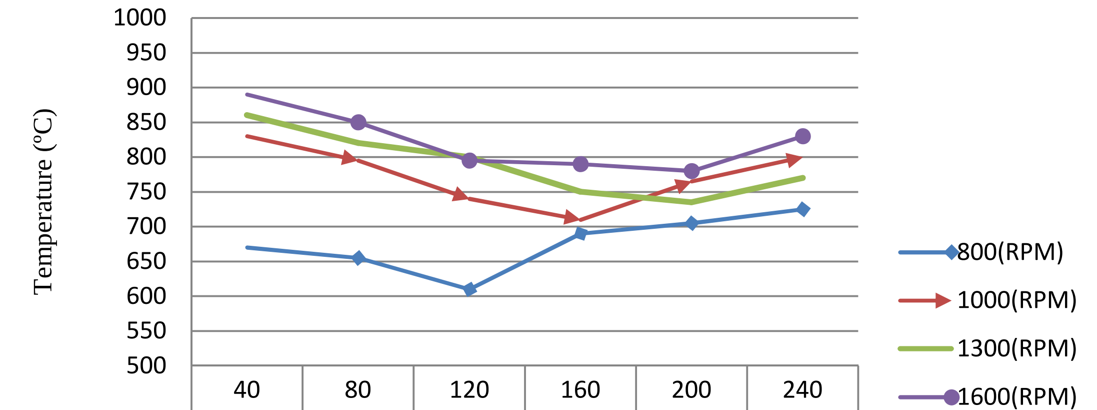
The results showing the effects of speed and feed rate on the bush length and temperature are presented in Figures 8 and 9 respectively. The results of the surface roughness are presented in Figure 10.



	40	80	120	160	200	240
800(RPM)	5.6	7.1	7.5	6.4	6.5	5.7
1000(RPM)	7.2	7.3	8	8.4	6.3	5.8
1300(RPM)	6	6.4	7.3	7.9	8.4	6.1
1600(RPM)	6.2	6.6	7.6	8.3	8.1	8.5

Feed (mm/min)

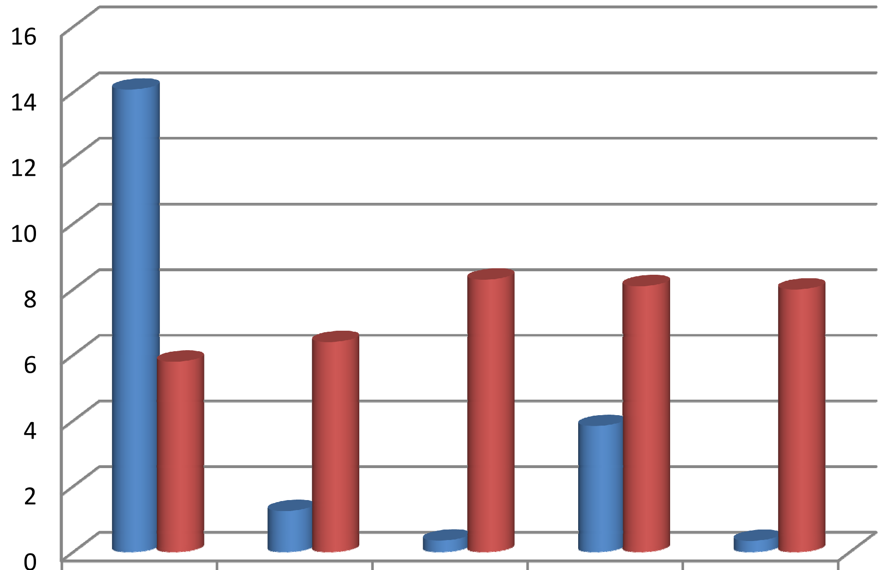
Figure8. The effect of the feed rate on the bush length



	40	80	120	160	200	240
800(RPM)	670	655	610	690	705	725
1000(RPM)	830	795	740	710	765	800
1300(RPM)	860	820	800	750	735	770
1600(RPM)	890	850	795	790	780	830

Feed (mm/min)

Figure9. The effect of the feed rate on the temperature



	A	B	C	D	E
Roughness Ra(µm)	14.09	1.252	0.351	3.842	0.342
Height of hole (mm)	5.8	6.4	8.3	8.1	8

Figure10. Bush height and surface roughness in the selected samples

3.1 The Effects of the Speed and Feed Rate

As the rotational speed increases, the friction increases and as a result, the temperature raises [10]. For drilling, usually, the temperature has to rise between 1/2 to 2/3 of the material's melting point [11]. The temperature is employed to soften the material so that the plastic deformation could be achieved. It is shown in previous studies, which in materials with lower heat conductivity; due to the heat concentration between the tool and the workpiece; it is better to have a constant speed and axial force, while the feed rate could be altered according to the temperature. In high feed rates, the bush height increases as a result of an increase in the momentum [12]. The optimum amounts of the speed and workpiece are 1000 rpm and 120 mm/min respectively.

3.2 The Effect of the Lubricant

To prevent the workpiece material to be welded to the tool, a high-temperature lubricant could be employed. Since this study is carried out on the titanium material which tends to stick to the tool, it is better to use the lubricant so that the temperature would decrease and the probability of production of the built-up edge is decreased. Therefore, the use of lubricant leads to higher tool life and better surface quality.

3.3 The Effect of the Tool Material

The process temperature at the beginning of the process rises up to 700 to 900 ˚C. For HSS tool material, since its maximum tolerable temperature is up to 700 ˚C and the heat conductivity of titanium is low, the tooltip is deformed before completion of the hole. Therefore the HSS material is not suited for frictional drilling of the titanium, while in previous studies it has been successfully employed for frictional drilling of copper and aluminum. The best material for frictional drilling of titanium is tungsten carbide, which has higher wear resistance and can be used in higher temperatures in comparison with HSS tools. On the other hand, because of the higher brittleness of the tungsten carbide, it is more sensitive to the machine vibrations. Therefore precautions have to be regarded to avoid the built-up edge formation in the process which exerts dynamic forces on the tool and causes some micro-cracks on the tool due to the difference between the expansion coefficients of the tool and workpiece materials [13, 14].

4. Conclusion

- The selection of the optimum amounts of the speed and feed rate of the frictional drilling depends mainly on the heat conduction of the workpiece material. In materials with higher heat conductivity, the speed has to be high and the feed rate should be lower. While in materials with lower heat conductivity, the speed should be decreased and the feed rate has to be increased.
- About the materials in which the probability of the built-up edge formation is lower, as the temperature rises as a result of the increase in the cutting speed and feed rate, the metal crystallization energy increases and approaches the metal's melting point and consequently the surface roughness decreases.
- High feed rates and selection of the feed rate regardless of the speed, results in insufficient softening of the material, which leads to incomplete melting of the material and sticking of the material on the tool which reduces the surface quality. Generally, the right selection of the speed and feed rate significantly excels the tool life and surface quality.
- In frictional drilling the thickness to the diameter ratio is very important, the higher the ratio, the higher the bush length and the compressive force. Furthermore, the higher bush length means the vaster contact surface between the tool and hole.
- The frictional drilling in presence of the lubricant excels the surface quality and increases the tool life; specifically about the titanium workpieces. The reason is that it prevents the wear by reduction of the friction and resulting heat.
- In frictional drilling, the tool has to be shock-resistant and wear-resistant. It should also be able to work in elevated temperatures, has good surface quality and resistant to vibration in order to produce high-quality holes and has a reasonable life.
- Because of the severe plastic deformation of the layers close to the hole surface, the hardness of these layers is higher than that of the other regions in the workpiece.

5. References

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