ANALYSIS OF THE FORCES AND VIBRATIONS EFFECTING ON CUTTING TOOL IN THE MICRO DRILLING OF TI-6Al-4V MATERIAL PRODUCED BY EBM METHOD

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Abstract: Thanks to its multiple usage areas, Ti6Al4V alloy is a highly preferred and researched material. Recently, with the development of additive manufacturing technologies, studies on this alloy have intensified. Additive manufacturing has recently become a very important alternative for designs that cannot be manufactured by traditional methods. Workpieces produced by additive manufacturing cannot be used directly in the areas of use. Because they may not have the desired features directly. Generally, various machining processes are applied after additive manufacturing. The most used of these processes are turning, milling and drilling. There are many reference studies on the processes of the parts produced with traditional methods. However, since the materials produced by additive manufacturing have different properties, they should be examined separately. In machining, cutting parameters, surface quality, tool life, labor costs, energy costs, geometric tolerances, etc. have a direct impact on many details. Microhole drilling is used in special fields (aerospace, defense, automotive, and medical). It is also a process that needs to be worked very carefully. Micro drills can break easily because they have very small diameters. In this study, cutting forces and vibration affecting tool life and quality were investigated. Ti6Al4V alloy produced with EBM was used in the study. Three different diameters (0.5mm, 0.6mm, 0.7mm) of micro drills were tested at different feed rates and different speeds in dry-cutting conditions. A 3-axis high-precision CNC workstation was used in the studies. Feed rates were chosen as 1, 2, and 3 mm/min. Three different spindle rotation speeds were tested (5000 rpm, 10000 rpm, and 15000 rpm).

Keywords: Electron Beam Melting, Ti6Al4V, Vibration, Micro Drilling, Cutting Forces, Additive Manufacturing

INTRODUCTION

Additive manufacturing (AM) is becoming more common day by day due to the advantages it provides (Karunakaran, 2010; 490-499), (Shamsaei, 2015; 12-35), (Bartolo, 2012; 612-635). Some of these advantages include freedom of design, no need for fixtures, avoidance of waste, and an excellent alternative for prototyping. The selective laser melting method (SLM) and electron beam melting method (EBM) are among the most preferred additive manufacturing methods in metal additive manufacturing. Titanium alloys are highly preferred in areas such as aerospace, defense industry, and automotive, thanks to their high strength in tough conditions. It is also widely used in the medical field, thanks to its compatibility with the human body. Therefore, Titanium alloys are the most studied materials in the additive manufacturing field (Trosch, 2016; 428-431). Titanium alloys are both light and durable materials and Ti6Al4V alloy is generally used in cockpits, accelerators, wings, and engines in aviation. Titanium alloys are highly preferred in the medical field, especially since they do not react with the body (Rong, 2016; 333-342). Thanks to the micro holes, assembly operations can be done. It is difficult to produce complex designs with conventional methods, and machining hard materials such as Titanium alloys makes the process even more difficult. Although additive manufacturing has many advantages, it is difficult to use the parts produced by additive manufacturing directly. The parts produced by additive manufacturing undergo processes such as turning, milling, drilling, polishing, and grinding to provide the desired properties. Micro holes are used in pressurized fluid passages and especially in

implants. Drilling is one of the post-processing processes after additive manufacturing, like other machining processes. Two major factors affecting the life of the drill and the quality of the hole are cutting force and vibration. In this study, micro holes were drilled under dry cutting conditions to find suitable micro hole drilling parameters with a carbide drill. There are many post-processing studies after additive manufacturing in the literature, but studies on microhole drilling are limited (Ming, 2020; 43-51). Drilling holes of the appropriate quality in materials produced by additive manufacturing is one of the biggest challenges facing industries (Karabulut, 2020; 355-359). Drilling studies larger than micro size are more common in the literature. In a study, the surface quality and geometric dimensions of the hole in the titanium alloy produced by additive manufacturing were investigated (Ilčík, 2014; 573-582). In another study, the surface quality of the hole was analyzed, and noted that the feed rate is significant (Vandenbroucke, 2007). Yusuf Kaynak and his teammate have studied the drilling process in additively manufactured Inconel 718. They worked on hole quality, microstructure, and surface roughness. They explored that increasing the feed rate provides quality surface and microhardness (Karabulut, 2020; 355-359). In another study, the micro-drilling study of Titanium alloy produced by the DMLS method was carried out (Rysava, 2016; 583-586). As a result of the research, it was determined that the amount of burr at the exit is higher than the amount of burr at the entrance (Rysava, 2016; 583-586). In his study, Dang investigated the cutting forces of Ti-6Al-4V alloy produced by the DMLS method under dry drilling conditions. He found that as the feed rate decreases, the cutting forces decrease (Dang, 2019; 749-758). The highest machining temperature was observed at 0.12 mm/rev feed rate and 1500 rev/mm cutting speed and hence it was concluded that higher production can be achieved at a higher cutting speed and feed rate (Dang, 2019; 749-758). In another study, the chip morphology of Ti6Al4V alloy produced by additive manufacturing was investigated under dry drilling conditions (Ming, 2020; 43-51). The chip emerging in the drilling process directly affects the surface quality and tool life. As a result of the research, it was seen that the chip morphology changed as the cutting speed changed (Ming, 2020; 43-51). In the studies, generally, subjects such as materials, drill diameters, surface quality, geometric position tolerances, cutting conditions, drill coatings, cutting speed, feed rate, and depth of cut were studied. Ti6Al4V alloy is used in very critical areas and is becoming widespread. In the field of metal additive manufacturing, it is one of the most used materials together with Inconel. Machining works on parts produced with traditional methods have been done since the past and are very common. There are structural differences between materials produced by traditional methods and materials produced by additive manufacturing. Therefore, it should be examined how the materials produced by additive manufacturing will behave in machining. Appropriate parameters must be found. Such analysis studies that have been done or will be made will contribute greatly to research and development studies. Microhole drilling is also normally a difficult process. In a hard material such as Ti6Al4V, the conditions become a little more difficult. Micro-sized drills are more fragile than normal. Many factors affect the quality of the hole and the cutting tool. These factors are coolant, cutting speed, drill coating, feed rate, speed, etc. are factors. Vibration and shear forces were analyzed in this study. It has been determined which factors should be used in which diameters.

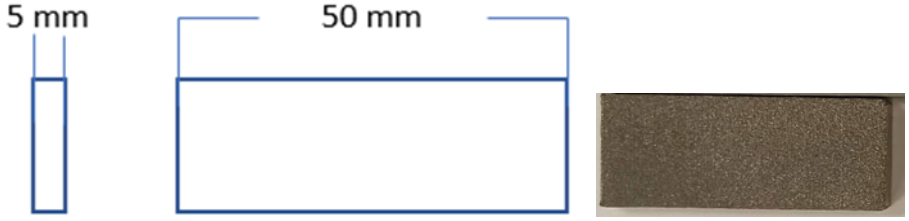

Figure 1. Sample and dimensions (mm) produced according to ASTM E8/E8M-13a standard

PURPOSE

Additive manufacturing has many advantages as well as some disadvantages. Parts produced by additive manufacturing are generally not used directly, they are subject to a second process. These operations can be milling, turning, and drilling. It is very important to use the right parameters to achieve the best quality and efficiency as a result of machining. Parameters directly affect surface quality, tool life, and geometric measurement accuracy. If the correct parameters are not used, the cutting tool may wear out early. Surface quality may be poor. Geometric tolerances may be inaccurate. These results cause extra costs, loss of workforce, and inefficiency. The biggest factors affecting tool life and process quality are cutting forces and vibrations. In the study, it was investigated which parameters are efficient in the micro drilling process of Ti-6Al-4V material produced by the EBM method.

METHOD

The general overview of the testing system is shown in (Figure 2). In the investigation of Electron Beam Melting (EBM), samples (as shown in Figure 1) were fabricated on an Arcam Q20 Plus EBM machine using Ti-6Al-4V material. The supplier was Arcam Company for material powder (Table 1). For parts production, standard 3.2.3 software has been used on the EBM machine. To produce EBM parts, preheating process is necessary. It is about 730°C. Table 2 contains EBM parameters to produce a part. The parts produced by additive manufacturing always have a rough surface. Therefore pre-machining has been applied to clean the surface by a CNC milling machine (It can be seen on the second machined part). One Ti-6Al-4V plaque part with dimensions of 50 mm 20 mm 3 mm was prepared for drilling. To achieve good surface, the milling method was applied to the part. The general system can be seen in Figure 2. As a cutting tool micro drill is inside the rotation booster. EBM material is fixed on the dynamometer. The vibration meter sensor is fixed by a magnetic connection. Drilling process photos were taken by the camera.

Table 1. Chemical composition of Arcam EBM Ti-6Al-4V powder

Elements	Al	V	O	Fe	C	N	H	Ti
Content	6%	4%	0.15%	0.1%	0.03%	0.01%	0.03%	Balance

Table 2. Parameters for the EBM

Melt	Surface temperature		925°C
	Contours	Beam speed	400-450 mm/s
		Beam current	7 mA
		Beam offset	0.18-0.27 mm
	Hatch	Beam current	35 mA

General overview of the system incluedes micro drill, rotation booster, camera, dynamometer system, workpiece and vibrationmeter. Explanation of the parts has been added every figure below.

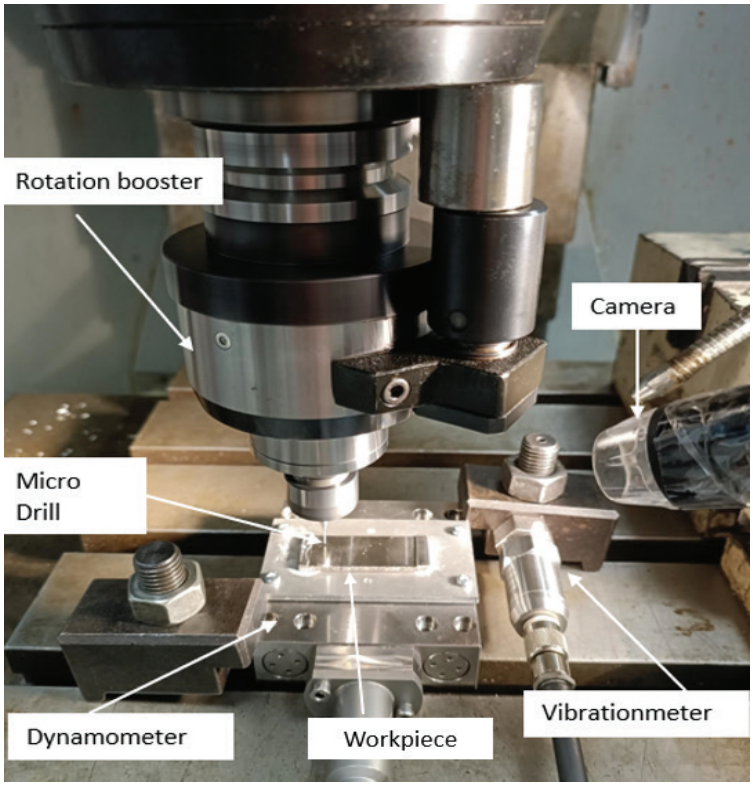

Figure 2. General overview of the drilling system

The drilling process is always hard to implement. Especially micro drilling needs a lot of features. The drilling tool has to be rigid and stable. To achieve a good result, modern machines should be used. In our drilling process study, a CNC milling machine was used as a driller. CNC milling machine operating software is Fanuc control panel. During the drilling process, the 3mm cutting thickness is kept stable.



Figure 3. Johnford VMC – 550 Model CNC Milling Machine

Table 3. Features of CNC milling machine

Model	VMC 550
Table working area	1000 x 500 mm
Motor power of milling	10 HP
Table weight capacity	900 kg
Machine area	2,35 x 2,5 m
Machine weight	5500 kg
X, Y, Z movement capacity	800 mm, 500 mm, 450 mm

CNC machine has a maximum of 3000 rpm. To achieve high rotation NIKKEN rotation booster was used. Rotation booster can increase rotation level by 5 times. Rotation booster also saves cost. While the machine work at its normal capacity rotation booster supplies more cycle. Therefore energy can be saved.



Figure 4. NIKKEN Rotation booster N X 5

As a dynamometer, a KISTLER 3D quartz device was used. It was used to measure the force acting on the three axes during drilling. The system consists of three parts. Three-dimensional quartz dynamometer, three-channel charge amplifier, stylus, and software for measurement analysis. Thanks to four sensors placed between two metal plates, it can measure force in the X, Y, and Z axes.

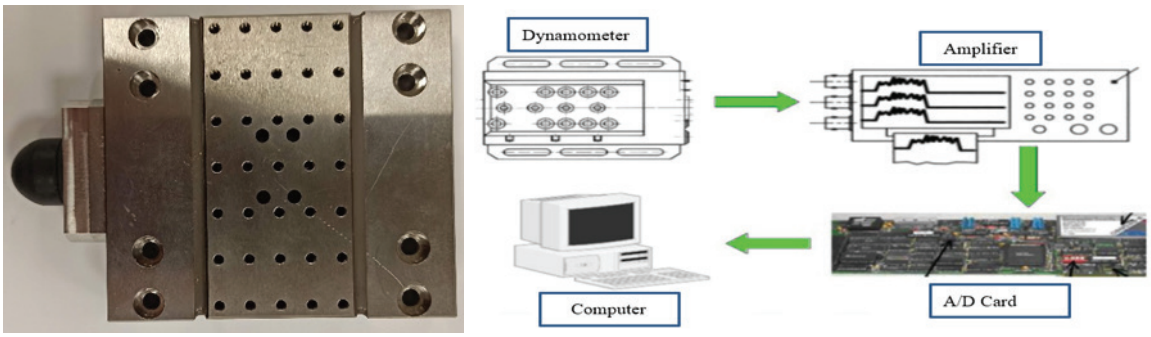

Figure 5. KISTLER Dynamometer and measurement schema

Cutting forces and vibrations directly affect the process quality and tool life. In our study, besides the cutting forces, the vibrations on the cutting tool during drilling were also measured. The vibration device has a magnetic sensor that can be attached to the surface to be measured. Measurements were taken by fixing the vibration measurement sensor to the dynamometer. The vibration level was measured by resetting the device for each operation. The maximum vibration level reached by the device during the measurements was taken as a basis.



Figure 6. SCHENCK Vibrotest60 device

Vibrotest60 has an analysis software called vibe report. It transfers the measurements made to the computer and analyzes the vibrations. Thanks to the device, the state of the machine can be analyzed. Precautions can be taken for a possible bad condition. In addition, process improvements can be made. To obtain an accurate vibration analysis, the environment must be tidy. There should be no equipment that affects the vibration.



Figure 7. Micro drills

Micro-sized drills were used during the drilling operation. The drills are coated Tungsten carbide drills. Thanks to the coating, high strength, high drilling performance, and efficiency are provided. The working speed should increase as the drill diameter gets smaller. Vibration and heating increase in drills as they work at high speeds. Especially in tough materials such as Titanium alloys, the probability of drill breakage is high. The drill set contains micro drills from 0.25 mm to 0.8 mm.

Table 4. Features of drills

Used Diameters	0,5 mm – 0,6 mm – 0,7 mm
Material	Tungsten Carbide
Flute Length	6 mm
Overall Length	35 mm
Shunk Diameter	3,25 mm
Point Angle	118 ± 5
Helix Angle	30 °

A high-precision CNC milling machine was used to obtain the most accurate result in the trials. At the end of each drilling process, the drill was changed and a new hole was drilled with the unused drill. During vibration measurements, no source will create a different vibration in the environment. In addition, it was waited for the piece to cool down at the end of each drill so that the heat generated on the workpiece would not affect the drill. Codes are written on the CNC control panel for the drilling process. No manual drilling was done. The program was used because there may be a human error-induced progress problem in the man Each drilling process was recorded using the software of the force measuring device. Measurements were taken from the beginning to the end of the drilling process. CNC software provides a stable and trustable drilling process.

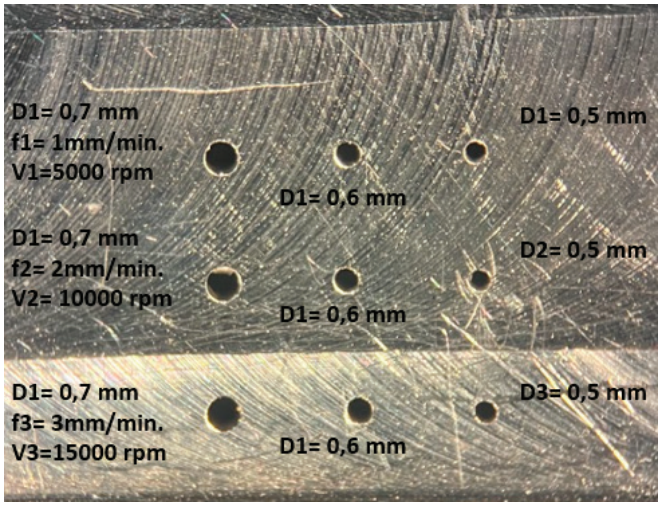

Figure 8. Micro holes in Tİ-6Al-4V workpiece

Three different drill diameters, three different speeds, and three different feed rates were used throughout our studies as you can see in Table 5. The workpiece thickness is 5 millimeters. The thickness has been reduced to 3 millimeters to be able to reach the other side of the part at the end of drilling. The channel was created by milling so that the edges remained 2 mm.

Table 5. Drilling parameters

Diameters (mm)	0,5 mm	0,6 mm	0,7mm
V1 (rpm)	5000 rpm	5000 rpm	5000 rpm
V2 (rpm)	10000 rpm	10000 rpm	10000 rpm
V3 (rpm)	15000 rpm	15000 rpm	15000 rpm
Feed rate 1(mm/min)	1 mm/min	1 mm/min	1 mm/min
Feed rate 2 (mm/min)	2 mm/min	2 mm/min	2 mm/min
Feed rate 3 (mm/min)	3 mm/min	3 mm/min	3 mm/min
Depth (mm)	3 mm	3 mm	3 mm

FINDINGS

The forces and vibrations measured during the drilling operations are listed below. The first drilling process took about three minutes. The maximum force and vibration values seen during the process are attached. The forces acting on the Z axis in the drilling process were investigated.

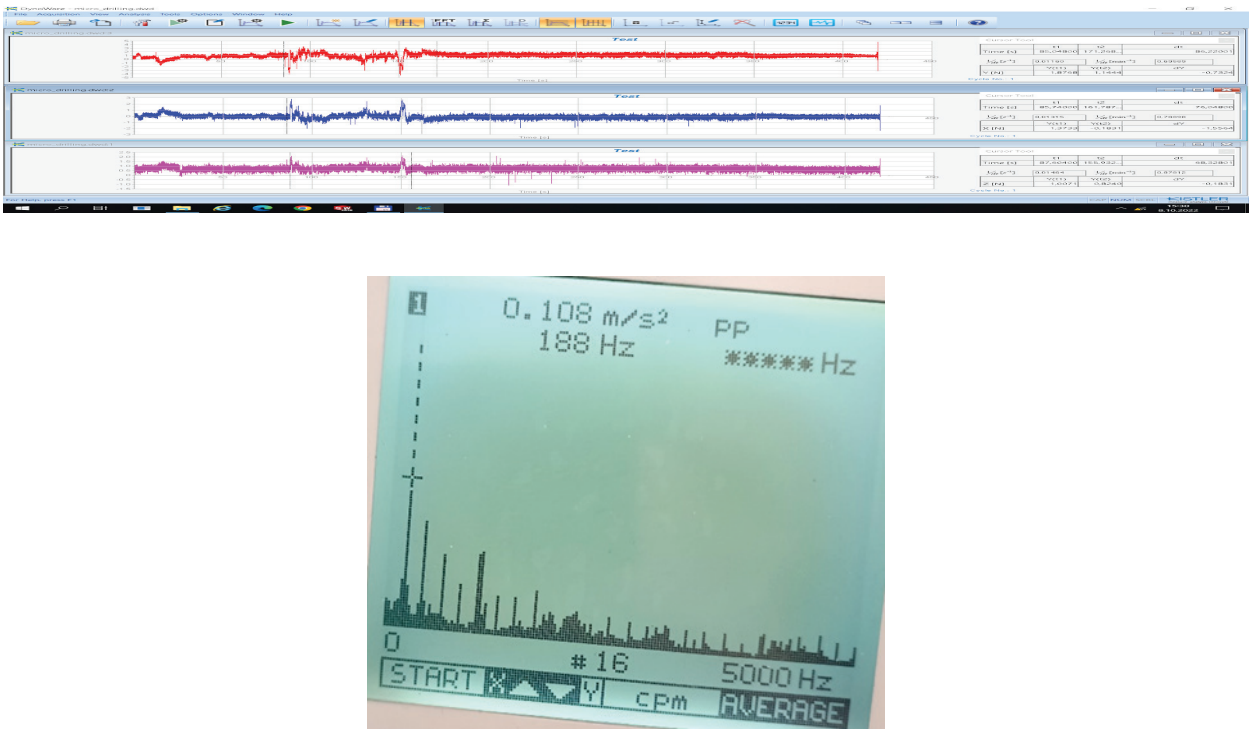

Figure 8. Sample of cutting force and vibration value of first drilling process

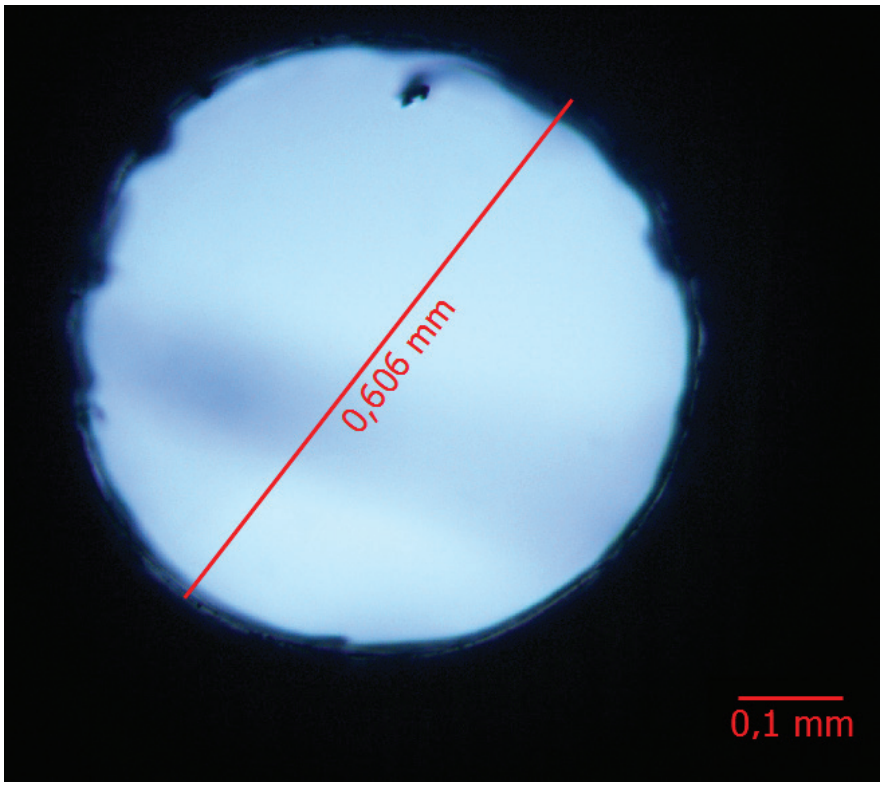

Figure 9. 0.6 mm hole image under the microscope

Table 6. General overview of the drilling studies

Diameter (mm)	Test Number	Max. Vibration (Hz)	Max. Z Axis Force(N)	Drilling Time (min)	Drilled Distance(mm)
0.5 mm	Test 1	188 Hz	0.701 N	3 min	3 mm
0.5 mm	Test 2	188 Hz	0.762 N	1,5 min	3 mm
0.5 mm	Test 3	234 Hz	0,964 N	1 min	3 mm
0.6 mm	Test 4	1750 Hz	0,809 N	3 min	3 mm
0.6 mm	Test 5	1969 Hz	1,232 N	1,5 min	3 mm
0.6 mm	Test 6	2000 Hz	1,526 N	1 min	3 mm
0.7 mm	Test 7	2000 Hz	1.007 N	3 min	3 mm
0.7 mm	Test 8	2969 Hz	1.464 N	1,5 min	3 mm
0.7 mm	Test 9	2969 Hz	1.901 N	1 min	3 mm

As can be seen in the table, the forces increase as the drill diameter increases. The main reason for this situation is the increase in the surface contacting the material. The cutting edges of the drill make more contact. The cutting forces acting on the cutting tool increase. At the same time, the amount of chip generated makes it difficult to cut. Heating of the material as the holes are drilled can cause ductility. This can cause chip to stick to the drill and make cutting difficult. The same situation will cause the vibration to increase. As the feed rate increases, the pressure on the material also increases. At the same time, force and vibration increase. The cut surface size also directly affects the vibration.

CONCLUSION

Many factors affect cutting forces and vibration. One of them is the rigidity of the cutting tool and fixture. A non-rigid drill or workpiece will cause force fluctuations and size differences. When tool diameter increase vibration and forces increase. But there is no dramatic change in vibration according to feed rate and tool cycle. According to results of the drilling trials, Vibration is not changing dramatically with cutting speed and feed rate. Therefore, we should focus on cutting forces. To decrease cutting forces feed rate has to be arranged with material and tool types. Optimum feed rate will provide minimum cutting forces, maximum tool life and quality. In addition, additive manufacturing processes are not like mass production. In mass production, it is aimed to produce a part as quickly as possible. However, additive manufacturing is currently a slow process and is often used for prototypes. Therefore, the feedrate can be chosen as the minimum to reduce the cutting forces. There are also some solutions for decreasing vibration and cutting forces. Cutting fluids help remove the cutting tool during the cutting process and prevent heating. In the next study, tests can be carried out using various artificial or environmentally friendly cutting fluids. Since cutting fluids facilitate the cutting process, the forces are reduced. Cutting forces directly affect the life of the cutting tool. Also, different drill materials can be tried.

REFERENCES

Bartolo, P., et al., Biomedical production of implants by additive electro-chemical and physical processes. CIRP annals, 2012. 61(2): p. 635-655.

Dang, J., et al., Experimental investigation on machinability of DMLS Ti6Al4V under dry drilling process. materials and Manufacturing Processes, 2019. 34(7): p. 749-758.