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OVERVIEW OF MACHINABILITY OF TITANIUM ALLOY (TI6AL4V) AND SELECTION OF MACHINING PARAMETERS

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Machining of titanium alloy Ti6Al4V is a challenging task for the industry; however, there are some solutions to overcome these difficulties. One of those is optimizing the machining parameters. Machining of Ti6Al4V made by additive manufacturing is an emerging future and is even more difficult when comparing to standard Ti6Al4V alloy. There is lot of invention on Ti6AL4V 3D printed samples, but influence of machining post-printing is lacking. In additive manufacturing of Ti6Al4V alloy, it is necessary to make a finishing operation to improve the surface quality and to ensure precise geometry tolerances. During this process, it may affect the workpiece properties such as microhardness, microstructure, internal defect distribution, internal stresses. During printing there are lots of stresses created, heat treatment is done to normalize the parts. Machining (using milling machine) also causes internal stresses which can damage the surface and part itself. Optimisation of machining parameters and printing parameters can solve this issue. This study gives an overview of selection of machining parameters by considering all the previous relevant research.

Keywords: *Additive manufacturing, adaptive machining, CNC milling, roughness, Ti6Al4V.*

1. INTRODUCTION

The demand for 3D printed titanium alloy parts is increasing widely especially in aerospace industry, medicine because of its high strength and low weight combination [1]. Even though these alloys are expensive, because of their high recyclability rate, the price is negotiable. It is reported that titanium alloys account for approximately 11 % of the fuselage structure weight of the Boeing 777, about 15 % of the Boeing 787 and in the fourth-generation jet fighter F-22 the weight proportion of titanium alloys is about 41 % [2]. In the past, the success of a machining operation was only valued in terms of product quality and cutting tool life, whereas today the most important criterion for success of an operation is its sustainability [3]. By 3D printing, the parts can be printed with precise dimensions, even though many parts require finishing operation to achieve the required surface quality and dimensional tolerances. To achieve the final product, the main problems are printing method and parameters, production time, and machining parameters and adaptability.

Depending on the type of printing method and technique, size of the part, preparing the part itself consumes a lot of time, which can be saved by introducing adaptive machining process for finishing operations. Regarding machining of titanium, much research has already been carried out, but still more attention is to be given to other machining parameters for cost efficient and optimised techniques [1], [4], [5]. During machining the chip gets weld to the tool due to high chemical reactivity of titanium alloy, thus leading to cratering and premature tool failure [6]. To overcome this situation, a proper cutting tool must be selected. The low thermal conductivity of these materials does not allow the heat generated during machining to dissipate from the tool edge. This causes high tool tip temperatures and excessive tool deformation and wear. Since the machining time and cost are high for titanium alloys, the 3D printing could be more focused on cost and time optimisation [7]. High speed machining (HSM) could be one of the preferred options for production times, lower costs, and better-quality products [4]. Adaptive machining is the second option to save the production time and reduce costs. During machining of titanium alloys, the machining parameters such as cutting speed, coolant, feed rate and depth of cut play a significant role because of hard machining nature. In case of machining of 3D printed parts, slow cutting speeds give better surface roughness for the parts made by ABS, and it is reverse for PLA due to high temperatures [8].

Machining of Ti6Al4V alloy made by additive manufacturing higher cutting speeds and feed rates results in poor surface roughness and high cutting forces [9]. For machining of 3D printed titanium alloys, these parameters are even more important because of multiple thin layers in the part. The heat generated during the machining may delaminate the layers and affect the structure of the workpiece. To investigate all these aspects, proper research with a precise analysis is required. In this research paper, an overview of machinability of Ti6Al4V alloy is presented and the selection of machining parameters is explained.

Table 1 shows the composition of Ti6Al4V alloy, consisting of such major components as 90 % titanium, aluminium 5.5 % and vanadium 4.2 %. This alloy belongs to $\alpha+\beta$ group and is known as grade 5 alloy.

Table 1. Chemical Composition of Ti6Al4V [8]

Chemical Composition	V	Al	Sn	Zr	Mo	C	Si	Cr	Ni	Fe	Cu	Nb	Ti
Weight %	4.2	5.5	0.062	0.003	1.005	0.37	0.022	0.009	<0.001	0.112	<0.02	0.0386	90

2. AN OVERVIEW OF MACHINING OF TITANIUM AND ITS ALLOYS

Titanium is the one of the toughest materials and challenging to perform machining. Despite recent developments and extensive usage of titanium alloys, machining of titanium alloys remains a major industrial concern because of short tool life, low metal removal rates, higher cutting force and temperature, and poor surface quality [5]. There are many parameters to be considered during the machining process. Due to titanium toughness, high cutting pressures are obtained and the cutters receive strong shock, which results in tool wear, damage to workpiece [1], [10]. Previous research suggests many tips to be followed while machining titanium. Titanium is tough and sticky material, so it is necessary to use a very sharp tool to avoid the interruptions. All the cutting speed and feed rates must be selected properly [1]. In general, the machinability of Ti6Al4V is better than Ti555.3 [11] and BTi-6431S [2]. The machinability of titanium alloy can be improved by using a preheating technique called high frequency induction heating [12]. The selection of process parameters is very important in machining [13]. A smooth surface with better MRR can be obtained with optimum combination of parameters [14]. Machining titanium alloys, the main parameters which are to be considered are cutting speed, feed rate, depth of cut, type of coolant, and type of milling tool.

Table 2. Overview of Machining Parameters and its Effects

Material	Operation type	Vc	dc	Feed rate	Tool	Coolant	Description	Ref.
Titanium and its alloys	Turning, Milling, Drilling	150, 300, 450	1.5 mm	0.03, 0.06 mm/tooth	-	Dry, Petroleum based coolant, MQL, Cryogenic cooling, HPC	Cooling methods and its effect	[3]
Ti6AL4V	Turning	45, 90, 180	0.5 mm	0.05, 0.1, 0.2 mm/rev	Tungsten carbide tool DNGG 150401-SF	-	With increase in Vc, cutting forces increased in SLM Ti6Al4V and decreased in wrought Ti6Al4V, also surface roughness improved. Better surface roughness observed in SLM T-6Al4V.	[9]

Material	Operation type	Vc	dc	Feed rate	Tool	Coolant	Description	Ref.
Ti6AL4V	Milling	80, 127, 200	1.0mm	0.088 mm/tooth	Polycrystalline diamond (PCD) inserts	-	Machining with induction heating – increased tool life. PCD inserts – tool life increased by 169.4 % during preheated machining at 650 ºC.	[12]
Titanium alloys	Turning	31.4 to 157	1.0 mm	0.11 mm/rev	Coated carbide insert CNMG120404-M5-Tp-3500	Dry	Tool wear mechanism. α alloys – abrasive tool wear. α+β alloys – material adherence on cutting tool. β alloys – deformation of cutting edge	[15]
Ti6AL4V	Turning, LAM, Hybrid	107, 150, 200	0.76 mm	0.075, 0.15 mm/rev	K68, KC5010	Liquid nitrogen (LN$_2$)	TiAlN coated carbide tool is 2 to 3 times better than uncoated carbide tool. Increased MRR, tool life and cost savings in hybrid machining process.	[16]
Ti6AL4V	Milling (up)	40– 80	1.0 mm	0.125, 0.15 mm/tooth	Sandvik^{R} TPMN 160308-H13A carbide inserts	Dry	For higher tool life and productivity feed rate 0.15 mm/tooth and Vc = 55m/min should be avoided. Development of AlTiN coated carbide tools.	[17]
Ti6AL4V	Milling	58, 63, 149, 154	-	0.1, 0.5, 1.5, 3.0 µm/tooth	2 and 4 fluted flat end square micro mills	Dry	Feed per tooth is the most influential parameter on surface roughness and burr formation. 2 fluted end micro mill produced better results than 4 fluted micro end mills.	[18]

Material	Operation type	Vc	dc	Feed rate	Tool	Coolant	Description	Ref.
Ti6AL4V	Turning	60*	-	0.08 mm/rev*	Coated carbide	Lubricant - Blaser Swisslube Vasco 5000, Dry	Effect of lubricant on tool life (increased by 40 %).	[19]
Ti6AL4V	Milling	100, 115	1.0 mm	0.075, 0.1 mm/tooth	Ingersoll CHIP SURFER D12 ball nose cutter	Dry, 30–100 % CO_2, Mineral oil-based emulsion	Advantages of cryogenic milling over dry machining and cooling lubricants.	[20]
Ti6AL4V	End milling	120, 150, 180	0.5, 0.75, 1.0 mm	0.05, 0.075, 0.1 mm/tooth	Kennametal 12A01R020A16ED10, d=12,0mm	-	Taguchi method. Cutting speeds – high effect on temperatures, and less effect on cutting forces. Vc = 150m/min, depth of cut = 0.75mm, feed = 0.075 mm/tooth is suitable for HSM.	[21]
Ti6AL4V	Micro-end milling	31.415	30 µm	0.5, 1.0, 1.5 µm/tooth	Two-flute tungsten carbide micro-end mill with d = 400µm	Dry	Cutting forces modelling by using ABAQUS / Explicit FEM method	[22]
Ti6AL4V	Turning	45, 60, 75, 90	0.2 mm	0.2 mm/rev	TPGH080204R-FS	-	Chip formation, tool wear, cutting forces. Machinability of Ti6Al4V is slightly better than BTi6431S	[23]
Ti6AL4V	End milling	30, 40*, 50 60*	2.0*, 2.5*, 3.0, 3.5 mm	0.01*, 0.015, 0.02, 0.025 mm/tooth	Kennametal (HARVI II) Solid carbide end mill d=6.0mm	Optimal amount of coolant	End milling – reduced cutting forces at feed 0.01 mm/tooth, Vc 40 m/min and depth of cut 2.0 mm. Best surface roughness at Vc= 60 m/min, depth of cut 2.5mm, feed 0.01 mm/tooth.	[24]
Ti6AL4V	Turning	45, 60, 75*	0.25*, 0.5, 0.75 mm	0.25*, 0.3, 0.35 rev/mm	PVD / TiAlN coated carbide inserts	Dry	Surface finish increased with increase in cutting speed. Optimal combination of machining parameters.	[25]

Material	Operation type	Vc	dc	Feed rate	Tool	Coolant	Description	Ref.
Ti6AL4V	Turning	75*	-	0.25mm*	PVD coated carbide	-	Use of Taguchi grey method for optimization. Cutting speed is the most important parameter influencing surface roughness.	[26]
Ti6AL4V	Turning	150*	0.25 mm	0.15mm*	Poly crystalline Diamond (PCD)	MQL	Taguchi method is used to compare the MQL cooling system with dry machining. MQL and PCD inserts are satisfactory tool materials for better surface roughness and hardness.	[27]
Ti6AL4V	Turning	90*, 120	0.8 mm	0.1, 0.2 mm/rev	Uncoated cemented carbide (CCMT 09 T308-KM H13A)	MQL, Dry, MQCL with rapeseed vegetable oil, cooled air, Flooded, Cryogenic	Comparison of lubricants. Proposed using vegetable oil.	[28]
Ti6AL4V	Turning	50, 60, 70*	0.02, 0.035*, 0.05 mm	0.01*, 0.02, 0.03 mm	Multi-layered CVD coated carbide tool	Wet cooling	Surface roughness and roundness.	[29]
Ti6AL4V ELI	Milling	200, 250, 300	1.5 mm	0.03, 0.06 mm/rev	TiAlN + TiN coated and uncoated carbide tools	Dry	Cutting forces decreased with an increase in Vc. Lower cutting forces observed with uncoated tools.	[30]
Ti6AL4V ELI	Turning	120, 170, 220	0.4 mm	0. 2 mm/rev	Uncoated carbide insert, CNGG 120408-SGF-H13A	Flooded (conventional cooling)	Highest tool wear is observed at cutting speed of 200 m/min and tool life is 2.3 min.	[31]
Ti6AL4V ELI	Turning	120, 170, 220	0.4, 0.5, 0.6 mm	0.1, 0.15, 0.2 mm/rev	Uncoated carbide insert, CNGG 120408-SGF-H13A	Flooded (conventional cooling)	Investigation on effect of Vc, dc, feed on surface roughness and tool life.	[32]
Ti6AL4V ELI	Turning	200 to 300	1.0 mm	0.2 mm/rev	-	Dry	Analysis of surface roughness, tool life, and cutting forces.	[33]
Ti6AL4V ELI	Turning	120 to 200	0.4 to 0.6 mm	0.1 to 0.2 mm/rev	Carbide cutting tool	Dry	Analysis of tool wear mechanism	[34]

Material	Operation type	Vc	dc	Feed rate	Tool	Coolant	Description	Ref.
Ti6AL4V ELI	Turning	55, 75, 95	0.1, 0.15, 0.2 mm	0.15, 0.25, 0.35 mm/rev	Uncoated, CVD coated, PVD coated carbide tools	Dry	Microstructure is significantly affected by high cutting speeds (95 m/min)	[35]
Ti6AL4V ELI	Turning	55, 75, 95	0.1, 0.15, 0.2 mm	0.15, 0.25, 0.35 mm/rev	TiAlN coated PVD inserts CCGT 12 04 02 HP	Dry	High surface roughness at high feeds but decreased with an increase in cutting speeds.	[36]
Ti6AL4V ELI	Turning	55, 75, 95	0.1, 0.15, 0.2 mm	0.15, 0.25, 0.35 mm/rev	Uncoated K313 (WC-Co), coated with PVD (KC9225), coated with PVD (KC5010)	Dry	Plastic deformation layer on machined surface was observed at Vc of 90m/min, feed of 0.35mm/rev, and dc of 0.1mm.	[37]
Ti6AL4V ELI	Turning	55, 75, 95	0.1, 0.15, 0.2 mm	0.15, 0.25, 0.35 mm/rev	CVD inserts (KC9225) (CCMT 12 04 04 LF)	Dry	Surface finish mostly affected by nose radius and feed rate. Coated cemented carbide tools produced surface finish is acceptable.	[38]
Ti6AL4V ELI	Turning	55, 75, 95	0.1, 0.15, 0.2 mm	0.15, 0.25, 0.35 mm/rev	CVD inserts with four layers of coating (TiN-Al2O3-TiCN-TiN)	Dry	Analysis of surface quality.	[39]
Ti6AL4V ELI	Turning	55, 75, 95	0.1, 0.15, 0.2 mm	0.15, 0.25, 0.35 mm/rev	PVD – TiAlN coated carbide tool	Dry, flooded	Influence of cutting parameters on machining.	[40]
Ti6AL4V ELI	Turning	120, 170, 220	0.4, 0.5, 0.6 mm	0.15, 0.2, 0.35 mm/rev	-	MQL, Flooded	MQL condition increased tool life by 25 %.	[41]
Ti6AL4V ELI	Turning	50, 65, 80	0.5 mm	0.08, 0.15, 0.2 mm/rev	PVD TiAlN insert. cNMG 120408-QM-1105	Dry	Surface roughness is 0.57 µm and cutting force 54.02 N was obtained at optimum cutting conditions (Vc = 66.97m/min, feed of 0.08 mm/rev).	[42]
Ti6AL4V ELI	Milling	75, 100, 125	0.3, 0.6, 0.9 mm	0.2, 0.25, 0.3 mm/rev	-	Dry	Effect of machining parameters on surface roughness.	[43]

Note: * indicates an optimal parameter. Vc – cutting speed (m/min), dc – depth of cut, MQL – minimum quantity liquid, MQCL – minimum quantity cooling liquid, LAM – laser-assisted machining, HPC – high pressure coolant, SLM – selective laser melting, FEM – finite element method, PVD – physical vapour deposition, CVD – chemical vapour deposition, ELI – extra low interstitials.

The selection of the cutting tool is very important by considering the properties of titanium. The design [44] of tool is very important to machine a hard material like titanium and its alloys. Most used tools are coated carbide tools which help improve the tool life [45]. The factors such as resistance to wear, good heat dissipation properties, ability to resist deformation, type of coating must be considered in the selection of a cutting tool [46]. During machining due to its elastic nature there is a high chance of material sticking to the cutting tool. To avoid such a situation, the tool must be sharper [1]. In case of 3D printed Ti6Al4V, this stickiness presents even more concern because of multiple layers which may result in delamination of layers and internal defects. Due to low Young's modulus, machining of titanium and its alloys has high tool bounce back, it results in stiffness and the tool bounces back from the workpiece. This can be controlled by fixing the tool very tight and tool overhang must be shorter so that it will not pull out due to high cutting forces, pressures, vibrations, and sticky nature of the material itself. [1], [10]. The radial engagement of the tool must be reduced to control heat. For finishing operations, the tool radius in contact must be in small percentage (small engagement) and feed rate must be minimal [1]. The use of coated tools does not show a considerable improvement on the machinability of titanium alloys. The BUE formation in α+β alloy reduces the effectiveness of tool coating [15]. However, a TiAlN [17] coated carbide tool is 2–3 times better than an uncoated carbide tool for hybrid machining [16] and with PVD coated carbide tool, lower temperatures and good surface quality are observed [47]. The cutting temperature and high pressure at the tool-chip interface, built-up edge (BUE) formation [12] [17] and the chemical interaction between the titanium and the tool are the main reasons of the tool wear [3]. An abrasion [13] due to BUE [18] was a major reason of tool wear in α+β alloy [15]. The adhered material is evident slightly more in two flute end mills than 4 flute end mills [18]; thus, an end mill with more flutes is recommended. Tool wear should be low enough to acquire high productivity. A sharp cutting tool with more flutes and small diameter for pockets, long cavities [48] is recommended in machining titanium and the sharpness must be maintained throughout the machining process. The tool radius must not be more than 70 % of that minimum internal radius to ensure plenty of room available for entering the cutting fluid [1]. The tool life can also be increased by using thermally assisted machining [12]. For higher tool life and great productivity, the combination of feed rate 0.15 mm/tooth and cutting speed 55 m/min must be avoided [17]. In Fig. 1, TiCN, Alpha, and TiAlN coated tools have high hardness [49] resulting in high wear resistance [40].

Because of titanium poor heat conductivity, it is hard to take away the heat from the workplace, so a high-pressure coolant can solve this issue [1]. Use of a high-pressure coolant is the best of all as it significantly improves the tool life [3]. By using a coolant in turning Ti6Al4V, the tool life increased by 40 % [19]. Some of the cooling techniques used were dry machining, conventional cooling system, minimum quantity cooling system (MQCL), minimum quantity of lubricant (MQL), cryogenic lubrication [3]. Dry machining is very difficult in taking away the heat resulting in difficulties in production. However, it is useful for sustainability and clean manufacturing. As no coolant is used in dry machining, the impact on environment is minimal. The use of petroleum-based coolants is very expensive, unsustainable due to its impact on environment and workers' health deterioration. MQL technique resulted in good surface roughness [50], cutting forces, improved tool life and minimal usage of coolant [49]. Cryogenic coolant technique results in better and smooth surface due to residue free coolant evaporation [20]. The usage of liquid nitrogen as coolant results in improved tool life, with 83 % increased MRR and better surface quality [51]. Cryogenic coolant [52] method is very promising; however, a combination of MQL and cryogenic coolant achieves great results [3]. Maximum tool life and auspicious machining condition is obtained by using cooling-vegetable oil on MQL [49].

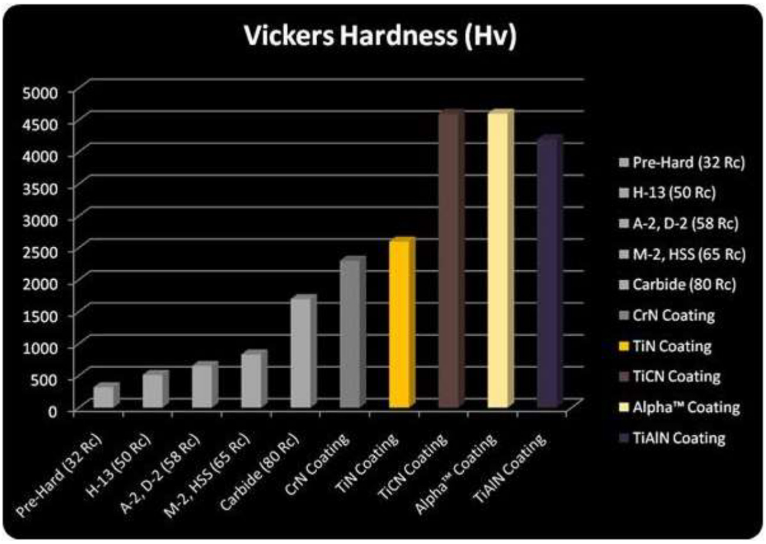

Fig. 1. Different coated tools with Vickers hardness [49].

The most favourable combination for cutting forces is high cutting speeds and low feed rate [13]. The cutting forces generated in machining of Ti6Al4V (α+β) are lower when compared to near α alloys [2]. Mechanical properties such as yield strength and hardness have reasonable influence on cutting forces [9]. The effect of feed rate and depth of cut on cutting forces is higher than the cutting speed effect, whereas cutting speeds have a high effect on temperatures [21], [53]. The cutting forces show a direct relationship with the cutting speed, feed/tooth and stepover, i.e., they increase with an increase in feed/tooth, cutting speed and stepover. The maximum cutting forces were recorded at a high cutting speed with a large stepover [8]. Cutting forces increased with an increase in cutting speed in case of machining of 3D printed Ti6Al4V and opposite in case of wrought Ti6Al4V [9]. From the previous experiments it has been studied that the tool wear is more in case of low-speed machining compared with high speeds. Cutting force is higher in case of a high cutting speed compared to a low cutting speed, which likely results in higher tool wear. An optimum feed of 0.15 mm with 150 m/min with MQL technique is recommended [49]. FEM can be used to simulate the temperatures and cutting forces [22]. In turning operation of Ti6Al4V alloy, the saw-tooth chips are formed at a cutting speed of 90 m/min [23]. At high temperature, work softening appears which makes machining easier but, at the same time, this elevated temperature also accelerates the tool wear and increases surface quality

[13]. Higher cutting speeds result in stable process [54] but have strong effect of tool vibrations on machined surface [18]. By using liquid nitrogen as coolant, the favourable cutting speed is 110 m/min resulting in 91 min tool life [51]. The recommended cutting speed for machining titanium alloys is 60 m/min [10] or less than 60 m/min [16]. For finishing operations, cutting speeds can be 180–240 m/min [10].

In case of machining titanium alloys, feed rate is very crucial as it has a huge effect on surface roughness [50], [55], [56] even with the usage of coolant. If the feed rate increases, the cutting forces increase [13], thus resulting in tool wear. Lower the feed rate, better the tool life, lower cutting forces, and surface roughness. In turning, the feed rate has the strongest influence on tool wear [19]. Low feed rates are recommended in case of high cutting speeds. With an increase in the feed rate, the surface roughness increases due to vibrations and thermal softening of build-up edges [9].

Depth of cut plays a huge role in tool wear and heat generation during machining of titanium alloys. Cutting forces increase with an increase in depth of cut [8]. Cutting forces become more stable at higher depth of cuts (1 mm), however the preferable depth of cut is 0.75 mm [21].

During machining, due to sticky nature of titanium alloys the formation of build-up edge chips [12], [15] is common, which results in faster tool wear and poor surface roughness. These build-up edges can be reduced by increasing cutting speeds, thus contributing to improved surface roughness [9]. Climb milling is one of the best solutions to perform machining on titanium [1]. In down milling, the chips formed are thick at the starting point of cutting and thin at the end point. The burr formation [18] is decreased by 50 % as speed varies from conventional to high speed [57], so that the initial heat will be carried away with chips. Another benefit of this type of milling is that the thin portion of chips does not stick to the tool.

3. CONCLUSION

By considering all these important parameters, it is known that machining standard titanium alloy itself is a challenging task, so one can understand the toughness level of machining titanium alloys made by additive manufacturing. Machining of additive manufactured Ti6Al4V alloys is an emerging challenge to be faced by the industry. Due to hard machining nature and limitations, it is very important to study the effect of machining parameters on surface roughness, distribution of internal stresses, behaviour of microstructure, internal defects, and mechanical properties.

To analyse all these important areas precisely, good equipment with precise readings is required. The internal defects, layer lamination and delamination can be analysed by using computer tomography equipment (CT scan), the surface roughness can be measured by 2D and 3D profilometers from Mitutoyo. In additive manufactured parts it is also important to study the flatness of the sample, which can be done by CMM machine from Mitutoyo. The machining will be conducted on both the wrought Ti6Al4V alloy and 3D printed Ti6Al4V alloy to compare both for giving appropriate results and solutions. Better surface roughness can be achieved with combination of high cutting speeds and low feed rates.

By considering all the previous research and suggestions in Table 2, the effect of machining parameters to be analysed are cutting speed, depth of cut, feed rate, coolant, cutting tool and type of cutting. Table 3 shows the suggested machining parameters for future research.

Table 3. Selection of Machining Parameters

Cutting tool	D = 6 mm end mill
Coolant	High pressure coolant
Cutting speeds (m/min)	70–240
Feed rate (mm/tooth)	0.01, 0.015, 0.02
Depth of cut (mm)	1.25
Stepover	15 %
Toolpath strategies	One-way, two-way, Helical
Milling type	Climb milling

The planned research will give an overview of effective machining parameters on internal stress and defect distribution in the additive manufactured Ti6Al4V alloy parts (the defect distribution and internal stress distribution is studied by using CT equipment), a solution to improve the mechanical properties and machinability of 3D printed Ti6Al4V alloy. This research is to be continued at Riga Technical University, Latvia.

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