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MACHINING DIFFICULTIES AND DETERMINANT MACHINING PARAMETERS FOR TITANIUM ALLOY

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M.S.M Yusop, A.Y.M. Said, Z. Karim, A.S. Ramli, I.H.A. Razak, M.Z.A Yazid: Machining Difficulties and Determinant Machining Parameters for Titanium Alloy -- Palarch's Journal Of Archaeology Of Egypt/Egyptology 17(9). ISSN 1567-214x

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ABSTRACT

Titanium is a major material for aircraft parts and components, particularly the body and engines. This material offers rigidity, strength and light in weight, that are significant in improving the payload capacity as well as fuel consumption of the jet engines. However, few restraints were identified in machining of titanium. The hard properties of this material which require high machining force, in addition the elasticity and poor thermal conductivity causing the machining of titanium parts becomes expensive and difficult. Due to these issues, proper important machining parameters were discuss to ensure the output of the machining is at optimum with the most cost effectiveness. These parameters were further discussed in this paper, reviewed from the various research paper and works, past research experiences and series of discussion with the titanium machining experts were explained and summarized.

1. Introduction

Titanium alloys are categorized under super alloy and known as hard and difficult to machine materials. There are four grades of commercial pure titanium that categorized by strength that can be used to meet the tasks and workability. As the most notable advantages of titanium alloys is the strength, it is perfectly suit for aircraft demand as the several important parts and components are made of titanium alloys [1]. Figure 1 shows the examples of aircraft parts and components that made by few types of titanium alloys in current aircraft development.

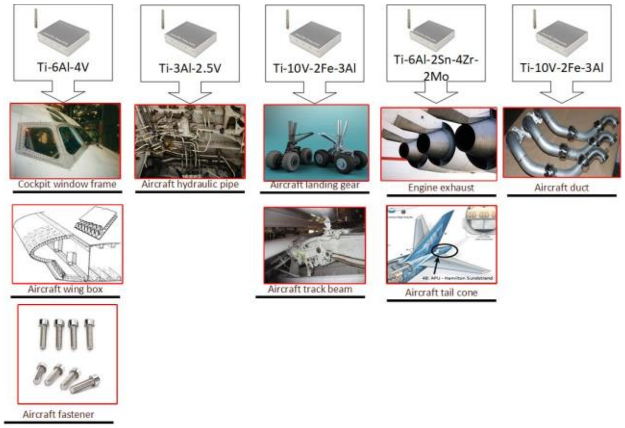

Figure. 1. *Example of parts and components made by titanium alloy in aircraft*

Titanium has highest strength-to-density ratio than any of metallic element. It is less dense than iron but high in strength, making it the preferred material and essential in aircraft development due to its lightweight feature [2]. This indeed the main purpose of the titanium alloys which to reduce the overall weight of a parts without losing its strength [3]. Lightweight characteristic is important to improve the fuel efficiency and to lengthen the flight distance of an aircraft. With current machining technology, latest high-speed thinwall feature machining path, the final parts weight may even be reduced [4]. Besides that, titanium alloys also offer good heat resistance for aircraft engine parts. Current commercial aircraft used titanium alloys in the compressor and for the fan in the fore half section where the working engine temperature are ranging from 600°C to 1100°C depends on models and sizes of the aircrafts [5] and for higher temperature area, Nickel based alloys is used to attain the heat generate from the engine.

2. Machining Dificulties

Apart of the advantages characteristic that titanium can offers, titanium alloy also consists of difficulties characteristic for titanium alloys machining. Plenty of research have been conducted in improving the machinability of titanium alloys and yet vast improvement needed to tackle in the difficulties issues in titanium machining. Figure 2 shows the list of difficulties in titanium machining.

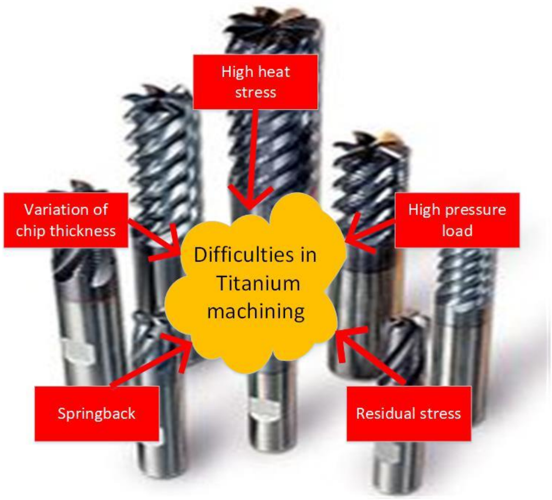

Figure. 2. *Difficulties in Titanium Machining.*

A. Springback

Springback is according to Song et al.[6], titanium alloys bound to have a springback effect due to its high ratio of yield strength to Young’s modulus. This was also acknowledged by Pramanik [7] as the machined workpiece tends to move away from the cutting tool unless deep cuts are performed or a rigid back up or special fixtures assists during the machining process. This thus leads to chattering effect towards the cutting tool than can lead to tool wear. Friction also occurred during machining as the result of springback characteristic in titanium alloys, which the cutting tool that chatters with the workpiece may increase wear on the cutting tools [8].

B. Residual Stress

Residual stress is a stress that contain in a stationary body at equilibrium after the external loads have been removed. It normally occurs during solidification of the titanium alloy when casting of the stock material [7]. Residual stress is extremely unsafe as the stress is able to extent if there is a crack occurs during machining, or usage that can lead to parts failure [9]. In addition, it also can accelerate crack nucleation, crack propagation, and corrosion reactions, which in turn may shorten the fatigue life of components that normally operated in harsh environments such as in high temperature in turbine aircraft engine. Residual stress is divided into two types of mechanisms; macro and micro stresses. Macro-stress can be found in titanium and that shows magnitudes vary with direction at a single point within a body. It is produced from several manufacturing processes such as metal forming, machining, joining and heat treatment processes. Micro-stress arise from the imperfection of a grain lattice in titanium structure that basically, in practice, machining process induce stresses that can cause the machined part to distort especially in the case of large structural components in aerospace industry [10].

Machining is a process where thermal and mechanical occurs as the cutting tool contacts towards the raw material. In fact, residual stress in machining is contributed from three different factors; mechanical loads, thermal loads, and phase transformations process. Figure 3 illustrates three different shearing area during a machining process. The red area shows the primary shear zone as this area focus on the tip of the cutting tool, enduring bulk plastic deformation. Whereas, the green area represent the secondary shear zone contacted to the cutting chips, while the yellow area shows the tertiary shear zone. As thermal and mechanical loads rise due to cutting process during machining, it leads to phase transformation called plastic deformation. As the machining continues it will completely transform into heat on the raw material, which contribute to residual stress formation [9].

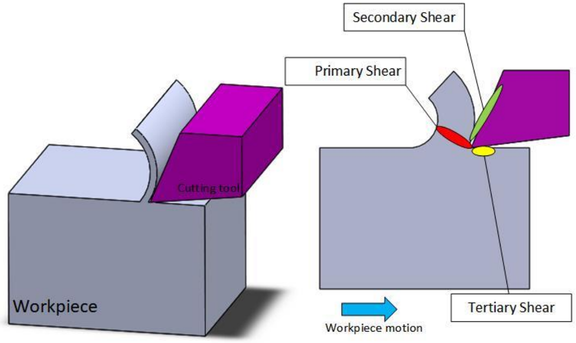

Figure. 3. *Main shearing area in machining process.*

C. Variation of Chip thickness

Titanium alloys are hard to machine due to the low thermal conductivity that determines several drawbacks such as plastic deformation and chemical diffusion between cutting tool and workpiece. Due to that, machinist are required to use moderate machining cutting parameters to ensure the maximum usage of cutting tool during machining [11]. According to past research [12] when the machining process was at or above critical cutting speed, segmented chips will be produced which involves localized shearing in associated with the generation of cyclic forces [13] and also produced an acoustic emission during the machining process. These varying thickness and width of cutting chips leads to rough surface finished, chatter marks and breakage of the cutting tool tip [14]. In other study, a developed thermal model for the thermoplastic shear of a titanium (Ti-6Al-4V) alloy carried out by [13] found that the freshly sheared surface of the cutting chips tends to rolls onto the cutting tool tip and this process developed an intense contact towards the cutting tool. As the machining continues, continuous chips were produced at or near the apex of the cutting tool tip with the chips segment for a considerable time as there is no relative motion between the chip segment and the cutting tool due to lump of ship segmentation. Furthermore, chemical content in the cutting tools may react actively with titanium causing the cutting tools wear rapidly.

D. High Heat Stress

In line of the titanium alloy characteristics, low thermal conductivity and high hardness features are another major machining issues that cause high cutting temperature that and leads to high heat generated at cutting tool and material chip which often troublesome to achieve an optimum production rate [15]. The research found that during low cutting speed at 60 m/min, temperature of the titanium alloy Ti6Al4V increased to 727°C and able to reach at 1077°C for 200m/min of cutting speed [15][16]. In addition, research conducted in [17][18] also obtained the similar result, which during machining at speed of 200 m/min, high temperature was generated at the chip–tool interface. This then initiated adhesion mechanism on the tool rake face and flank face as evidenced by plastic flow of the machined material. The adhesion thus worsen the cutting tool life, produced poor surface integrity and low in dimensional accuracy because of the high heat stress during the machining process [19]. In order to overcome these issues, high speed machining was preferred as in [20][21]. A study conducted by [22] had also proved the capability of high speed machining to dissipate heat with cutting chip during machining of aluminum alloy for aerospace material.

E. High Pressure Loads

Most of titanium alloy machining are difficult and have a time consuming process. It is due to the extremely hard material and it is necessary to have high cutting force to machine the material. High machining force increased as the depth of cut was found as the main effect of the increased of the high cutting loads [23]. During a machining process, the cutting tool experienced high pressure load on the cutting tip that will gradually reduce the cutting tip performance as high temperature would inflict the sharpness of the cutting tip. The stress on the cutting tool edge was also high with the increase of machining cutting speeds due to minimal contact of machining length and shearing angle during machining process [24].

3. Machining Parameters And Consideration

Past research and traditional techniques relies on using low cutting speed, high feed rates, depth of cut and using flood techniques of cutting fluids for titanium machining process. This conditions need to be applied with a sharp cutting tool which need to be replaced frequently as initial wear is usually detected during a machining process. This however is difficult as a machining process require vibration free. As demands for aerospace components and parts are increasing rapidly, these techniques however are not economical and consume high machining time. Nowadays, there are many other methods and techniques to improve the machinability and productivity of titanium machining. Current research and techniques focusing on four considerations and machining parameters in determining the best titanium machining setups illustrated in Figure 4. The main consideration namely as design complexity, machining technique, cooling technique and cutting tool selection and setup.

A. Design Complexity

Most aircraft parts and components are consisting of complex design and shape, including thinwall features. Part complexity can be defined by how sophisticated the part's and component's shapes and features towards its functional ability in an aircraft assembly. Thus, the complexity of the parts and components may directly influence to the machining plan and setup time [25].

Machinist usually prefer to apply single machining setup for most of the machining process in order to avoid misalignment and control the machined parts’ accuracy. Due to the complexity of an aircraft parts and components, the machinist is required to study the machining plan before executing the machining process.

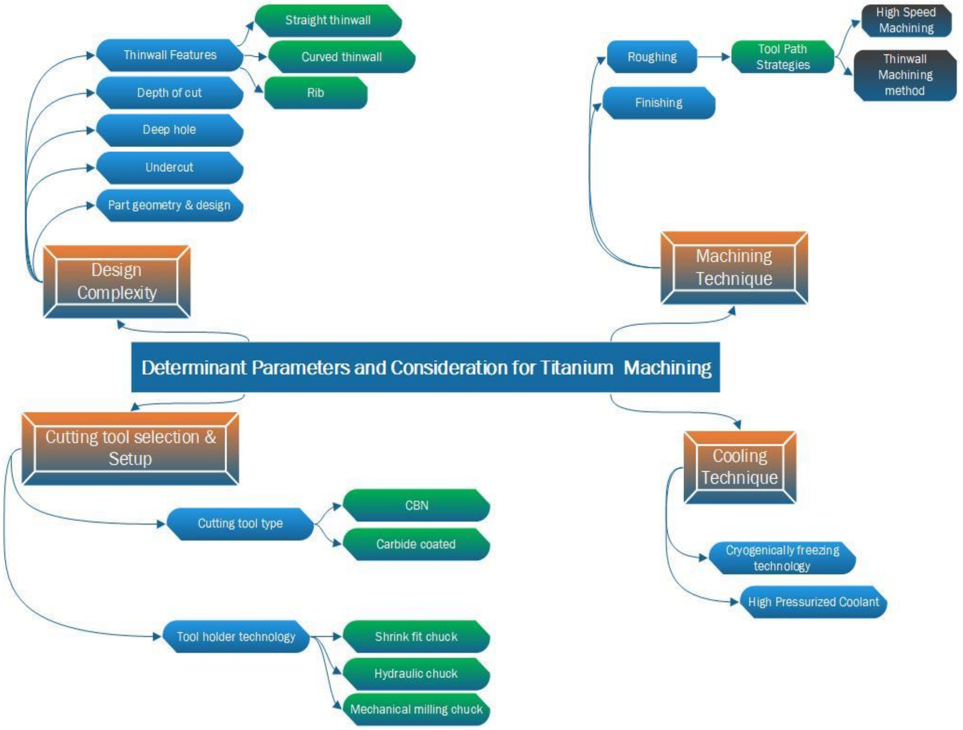

Figure. 4. *Determinant parameters and consideration for titanium machining.*

Aircraft nowadays is able to travel for longer distance due to the improvement of the overall weight of the components and parts. The usage of ribs as well as straight and curved thinwall features, for instance, improve the aircraft performance towards the fuel consumption for each flight as these features offers lightweight without compromising the overall parts and components strength [26]. A proper machining plan however is required as ribs and thinwall features are normally designed with 1mm thickness of the profiles, which machining vibration might affect the dimensional accuracy and result in poor surface quality [27]. In addition, acoustic emission happen as the cutting tool deflected towards the thinwall profile and becomes critical as the cutting tool easy to fail in achieving the final dimension as the deflection is highest as the thinwall become thinner [27]. It is important to determine the depth of cut in machining titanium. A study from [23] signifies the depth of cut as when it increased the cutting force was relatively higher because the increasing volume of the material removal process. Similar issue for deep drilling titanium process if neglecting the pecking distance clearance that leads to the increased the cutting tool wears.

B. Cooling Technique

The development of cutting fluids technology improves a machining process as the cutting fluids become an essential additional substance during machining process in order to get high productivity and quality of the machined part [28]. The cutting fluid is important as coolant to remove heat during machining operation and cool down the cutting area. It also is function as a lubricant, which to reduce friction and the tool wear [29][12]. In addition, cutting fluid also helps to flush the chips away from the cutting zone so that the chips will not attached or welded on the area, thus improving the final surface finish of the machining part. There are two methods of applying the cutting fluids in machining, which are high pressurized coolant and cryogenically freezing technology.

High pressurized coolant is the most effective method and widely used for titanium machining. In the operation, a water soluble oil based is pressurized ranging from 6 bar up to 90 bar high. The purposed of the high pressure is to ensure the cutting fluid is able to penetrate between the cutting tool and workpiece interfaces during machining towards the secondary shear zone [7]. This method is able to increase the cutting tool life by three times as it is able to reduce the surface machining temperature during the cutting process. This method is also can be further improved as the cutting fluids properties have better performance such as the thermal conductivity, lubrication ability and convective heat transfer coefficient technology [30].

The second cooling technique is called cryogenic freezing technology. The process was the suitable gases were spray towards the raw material and the cutting tool that create rapid cooling during the machining process. There are two types of suitable gases available for this technique, namely carbon dioxide and nitrogen. This method is able to improve titanium machinability drastically as a research conducted by Suhaimi at el. [31] was managed to reduce the machining cutting force by 54% and the cutting tool life was increased by 90% compared to the conventional cutting fluid applications. The vast improvement was due to the cutting tool did not exposed to high cutting temperature as the cryogenic freezing technique was able to offer machining process at low temperature. However, there is a major disadvantage of this method which the workpiece is hardened due to lower machining temperature cutting fluid. Because of this, the titanium machining requires higher machining force and possibly leads to cutting tool failure.

C. Machining Technique

A proper machining planning and strategies are important for titanium machining in order to ensure the process was done at minimum cost and shortest machining time. A proper machining planning will also producing parts and components in a more efficient and productive approach [32]. Roughing machining technique is normally used to remove most of the excess material. Latest CAM technology is able to offer various tool path strategies in order to fulfil the machining process. A suitable machining path will be chosen to maximize the machining area with the assist of CAM software. Roughing technique can be done by applying high speed machining process (HSM), which widely been used in combination of specific cutting tool, high machining speed and feed to achieve machining capacity and objectives [33]. Most of the HSM can also been applied in machining a thinwall profile especially for aviation components and parts due to long aluminum or titanium design [34]. As for finishing machining procedure, it is importantly to consider the minimum material removal to achieved good surface quality and dimensional accuracy and for finishing the thinwall feature to minimize the machining error as the thinwall deflects and chatter during machining [35].

D. Cutting tool Selection

There are several types of cutting tool that meets the requirement of titanium machining, namely cubic boron nitride (CBN) and carbide coated. Each of these types offers different advantages in titanium machining process. Burhanuddin [36] claimed that the CBN is useful when the feed rate was found to be the most significant factor to tool life, followed by cutting speed, depth of cut and the CBN grades. The research also found that the overall machining process was more affected when changing of the depth of cut, cutting speed and feed rate with lower CBN grade as the CBN cutting tool life able to operate at temperature at range 700 C [37]. As for carbide coated, there are two methods of coating offered in the current market known as chemical vapor deposition (CVD) and physical vapor deposition (PVD) cutting tools. CVD cutting tool has thicker coating and designed with a medium-sized grain structure. The advantage of this cutting tool is it is able to resist shock and prevents breaking during machining. The PVD on the other hand has thinner coating and designed with a finer structure in the tool material. The advantage of this cutting tool is it is able to perform uninterrupted smooth cut due to finer coated grain layered the core of the cutting tool.

E. Tool Holder Setup

In titanium machining, it is important to ensure that a combination of tool holder with a proper cutting tool is suitable as the machining will produce high cutting force due the toughness of the material properties itself. The advancement of the current tool holder technology was efficient as there are various choices can be made in the titanium machining. There are three types of tool holder and mechanism in the current technology; that are mechanical milling chuck, hydraulic chuck and shrink-fit tool holder system. The mechanical milling chuck is a common form of tool holding device. The most significant advantage is flexibility to hold any type of round shank tool. It uses self-extracting collet, which eliminates the purpose of the collet squeezers to extract the collet by any other means than screwing the nut off. The second type is the hydraulic tool holder and chuck. Hydraulic chuck is accurate, simple to use and offer robust tool holding capabilities. It is used for heavy milling that requires three times the clamping force of conventional hydraulic chuck systems. The chucks have a dampening capability which improves tool life, especially when machining titanium and other high-temperature alloys. The third holding method is called Shrink-Fit Tool holding.

The heat shrink technology uses thermal expansion, caused by an induction coil, to insert the tool and clamp it after cooling by a press fit thus implies low damping for this system. Hossain and Ahmad [38] conducted a comparison result between hydraulic and heat shrink technology, mentioned that a positive impact of the hydraulic chuck technology was better. The cutting tools clamped in hydraulic chuck technology showed significantly higher cutting tool lives of 300% compared to shrink technology at 100% range.

4. Conclusion

An investigation had been carried out to understand the machining difficulties and the important determinant parameters to improve the productivity of titanium machining processes. The main problem of titanium alloy machining is mainly on the high cutting tool wear in addition the chatter issue due to variation of cutting chips thickness. The machining also produces high heat stress as well as machining force which causing low material removal rate that leads to upturn of machining cost. Besides that, worsen quality of the final machining part, spring back and residual stress issues also need to be highly considered since titanium ribs and thinwall features will be affected if detail machining planning are not properly determined. In fact, each types of titanium alloys have different machining parameters to suit its machinability. For instance, machining of different titanium alloy grades producing different chip thickness, depending to the titanium’s hardness that also influencing the machinability. Therefore, a detailed machining plan is important before a machining process can be conducted. The planning should include the detail study of the parts and components design complexity consideration to ensure minimum machining setup, controlling parts accuracy and producing parts within machining tolerance. It is also important to plan the CAM machining path and technique to maximize the material removal rate for the machining time. Furthermore, various kind of cutting tool materials may chemically react towards titanium alloys during machining process. Suitable cutting tools such as carbide and CBN types was used for machining of titanium alloys in maintaining the machining output. A combination setup from a good cutting tool holder also ensuring the machining accuracy. In terms of the tool setting, a basic mechanical milling chuck is sufficient but both the hydraulic chuck system and heat shrink tool holder are appropriate in ensuring the machining accuracy and tolerance. In addition, an appropriate high pressurized coolant application is the common practice in assisting the titanium machining productivity. However, cryogenic cooling method can also be found useful during titanium machining, but a proper technique need to be further explored and studied as this method was found to have an issue due to rapid cooling is able to damage the cutting tool during the machining process.

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