Green Machining of Thin-Wall Titanium Alloy

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Preface

Sustainability is a global concern these days. The United Nation's intervention has accelerated sustainability drive worldwide and encouraged involvement at all levels. Manufacturing sector, where fabrication, machining, and materials processing are the major activities, is also busy inventing, developing, and implementing sustainable techniques.

This book provides a comprehensive collection of information and research work conducted on innovative sustainable techniques developed in various segments of manufacturing for improved quality, productivity, and sustainability. It consists of eight chapters on sustainable manufacturing. Chapter "Dry and Near-Dry Machining Techniques for Green Manufacturing" describes dry and near-dry machining techniques for green manufacturing, where innovative minimum quantity lubrication-assisted machining and dry cutting techniques with some case studies are discussed. Chapter "Cryogenic machining" provides a comprehensive information on cryogenic coolant-based sustainable machining. It reports a detail on the influence of cryogenic environment on machinability. Chapter "Sustainability Issues in Electric Discharge Machining" is dedicated to sustainability in electric discharge machining where the performance analysis of green electric discharge machining with the help of an experimental study is done. Chapter "Energy-Efficient Casting Processes" sheds light on sustainability interventions in casting. It is mainly focused on energy-efficient casting processes. Sustainability in additive manufacturing is focused in Chapter "Research Framework of Sustainability in Additive Manufacturing: A Case of Fused Deposition Modeling." A life cycle energy analysis of fused deposition modeling techniques is discussed. Sustainability concerns in various welding techniques are highlighted in Chapter "Sustainability in Welding and Processing." Chapter "Green Machining of Thin-Wall Titanium Alloy" presents green machining of thin-wall titanium and latest technology on the treatment of exhausted cutting fluid. At last, sustainability assessment-based comparative evaluation of gear manufacturing techniques is provided in Chapter "Sustainability Assessment-Based Comparative Evaluation of Precision Miniature Gear Manufacturing Processes."

The present book is intended to facilitate the researchers, engineers, technologists, and specialists who are working in the field of advanced and sustainable manufacturing. It intends to encourage researchers to go for research, development, and innovations with an objective to find the sustainable solutions to the problems encountered in the manufacturing sector by keeping the environment clean and green.

I sincerely acknowledge Springer for this opportunity and their professional support. Finally, I would like to thank all the chapter contributors for their availability and valuable contributions.

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Kapil Gupta

Contents

Green Machining of Thin-Wall Titanium Alloy

Amrifan Saladin Mohruni, Muhammad Yanis, Erna Yuliwati, Safian Sharif, Ahmad Fauzi Ismail and Irsyadi Yani

Abstract Titanium and its alloys are well known as difficult-to-machine materials due to low thermal conductivity and chemical adherent to cutting tools. Ti6Al4V is most widely used in a thin-wall structure application in the field of aerospace industry. Thin-wall machining encounters vibration and that furthermore increases fluctuations in cutting force. Select the type of machining process that generates sustainability in thin-wall machining is crucial to master. One of the innovations in conventional machining is to promote vegetable oils as the cutting fluids. These cutting fluids offer environmentally friendly cooling as well as lubrication to foster the cleaner production in the aerospace industry. Hence, the capable, sustainable cutting fluid has to be a future of the machining process. Minimum quantity lubrication (MQL) using coconut oil is recognised to be the green machining technique in milling titanium alloy. Coconut oils as nanofluids are attracting considerable attention due to good lubrication properties, non-toxic and biodegradable nature, and easy recycling. Therefore, it is a significant finding to observe the stability, dynamic behaviour, surface quality, and environmental aspects of cutting fluids in milling thin-walled Ti6Al4V. The findings reported in this chapter show

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that the use of coconut oil in the MQL system for thin-wall machining of Ti6Al4V is a promising innovation in the future of aerospace industries. At last, this chapter also sheds light on the treatment of exhausted cutting fluids.

Keywords Thin wall · Titanium alloy · Vibration · Surface quality
MQL · Nanofluids · Sustainable cutting fluids

1 Introduction

Cooling and lubrication are prime requirements in any machining process; therefore, cutting fluids play a pivotal role in machining. Cutting fluids cool, lubricate and thereby reduce the friction and heat generated in the machining zone. Even though cutting fluids have a reasonably low cost, their handling and carrying costs are very high, and their toxic nature and disposal are challenging [1]. It compels to choose the type of processes that are sustainable i.e., productive, clean, and green.

The primary means to control the tool wear propagations are to master the lubrication and heat removal rate in the machining process. One of them is the use of flood-cooling system. Although this system was proven at lower cutting speed, a decreasing performance occurs at higher cutting speeds. This phenomenon is caused by the high amount of heat generated in the critical areas (tool–workpiece interface), which cannot be reached by the cutting fluids; hence, the interface cannot be cooled. Ecological hazards, carbon cycle, operator's health issues, and mineral oils rising cost have brought to the utilisation of vegetable oils [2].

This limitation led to the use of MQL and cryogenic system in machining. The use of MQL, which required the gasification of oil mist, can absorb heat in the cutting area effectively. Another advantage of MQL is economical costs and an environmentally friendly technology. Nowadays, many researchers are trending to shift to use the vegetable oils as the cutting fluids. It possesses a higher boiling point, higher flash point, and excellent lubricity properties, hence lesser loss in the oil mist [2].

Initially, almost all of the research regarding machining on Ti6Al4V all this time were focused on high-speed machining, which followed by the technique, that enables the applying of the dry-cutting condition. Furthermore, the development of machining on Ti6Al4V leads to the utilising of vegetable oils as cutting fluids, mainly palm oil. Unfortunately, the abundance of palm oil could not cover the fact that palm oil contains at least 50% unsaturated fatty acid [3]. The limitation of this property affected the palm oil tends to be oxidative. The result of conventional machining on Ti6Al4V indicated the use of vegetable oil suitable for low and medium speed [4–6].

Current studies in thin-wall machining are focused on the use of finite element method (FEM). This approach was utilised in the analysing of stress distribution, deformation, mechanical vibration, geometric accuracy, and surface quality [7–10].

The important factors such as variable cutting force, tool deflection, and machining stability are not taken into account in the existing FEM models. There is a lack of information concerning the thin-wall machining of Ti6Al4V using vegetable-based nanofluids as a lubricant and the treatment of wasted cutting fluids. Therefore, it is essential to evaluate the performance of thin-wall machining on Ti6Al4V under MQL using coconut oils as nanocutting fluids and the potential treatment of wasted cutting fluid before it delivered to the environment.

Thin-walled structures are common useful part of modern aircraft, such as the integral panel, framework shells, and thin-walled membranes to improve the equipment performance by designers [11]. Thin wall is defined by [12] to mean a typical machining process that forms a piece of specific height-to-depth ratio approximately 15:1 and wall thickness approximately 3–5 mm. Ti6Al4V is the most widely used titanium alloy in thin-wall design requirements.

Titanium materials have received much attention due to superior corrosion resistance and mechanical properties such as high strength, light weight, high wear, fatigue strength, tensile strength, and wear resistance. Hence, these materials are recommended for use in the aerospace and automotive industries. Titanium alloy also has much applications in the field of energy, biomedical, shipping, chemical vessel, turbines, and electrochemical industries because of its higher structural efficiency characteristics [13, 14]. However, the high temperature strength combined with the low thermal conductivity contributes to the poor machinability [15]. Thus, the Ti6Al4V is well known a typical difficult-to-cut material. This problem caused difficulties in dissipating the generated heat in the contact zone. It leads to the very high temperature condition, which occurs in the tool tip and severely impairs their machinability [14].

The first description and evidence of chatter were performed in 1907 by Taylor [16]. However, the regenerative chatter theory reported by Tobias at the 1950s is the first systematic study in this field [14]. Researchers explained regenerative chatter in orthogonal cutting and developed a stability lobe theory for a two-dimensional case in the 1960s. A new analytical form of the stability lobe theory for milling presented in the middle of 1990s. More recently, some research obtaining the stability lobe diagram of a chatter system with consideration of the change of cutting position and the changes of workpiece mass and stiffness during the milling process [17]. For example, [16] obtaining the stability lobes method. Thus a three-dimensional lobe diagram has been developed base on the relative movement of systems.

Low heat conductivity [18] reduced rigidity [11] and complex structure [17] of thin-walled titanium alloy parts are the primary cause of unwanted vibration during the machining process. The limitation in high-speed thin-wall milling of titanium alloy is caused mainly by occurring of a robust regenerative vibration known as chatter. The chatter is the leading cause of the machining process instability, tool wear, and inferior surface finish in the vertical milling of thin-walled Ti6Al4V [14]. Conventionally, the cutting speeds in machining of titanium alloys are often limited to 60 m/min. Thus, it also gives rise to enormously increasing machining cost [14]. Cost efficiency, sustainability, high productivity, and product quality are the major focusing factors in manufacturing industry these days. To fulfil the aforementioned, machining operations should have high material removal rate, energy, and resource efficient, tighter surface tolerances [19].

A central problem limitation which prohibits obtaining high productivity and quality of workpiece is the chatter effect which leads to the chatter marks on the surface, and such a result may be a prominent issue for high-speed and high-precision milling processes [17]. The surface topography indicated by [14] has an association with cutting vibrations. The flexibility of workpiece and system tool was investigated by [16], under the action of the cutting forces that produce a vibration, giving rise to an irregular surface or wavy. The cutting force signals in thin-wall milling analysed using Fast Fourier Transform (FFT) was reported by [14] for detecting chatter phenomenon. The theoretical chatter model proposed by [11] taking the stiffness characteristics of tool and workpiece into consideration aiming at the titanium thin-walled parts. The prediction seems to be a useful approach. Another research was carried out by [18], which propose to study the influence of the tool entering angle on the stability of the process and tool life based on cutting force in milling Ti6Al4V.

Many machining technologies have been focused on reducing the cutting zone temperature, in order to improve the machinability of the materials. In industrial practise, the cutting speed used to machine these difficult-to-cut materials is insufficient. Mainly, MQL and cryogenic machining have been employed to enhance the machinability of the materials through providing lubricity and suppressing high heat generation on the cutting surface during machining process of hard-to-cut materials, respectively [13].

The sufficient cooling system for controlling the cutting temperature in machining is significant for the tool life improvement, especially when dealing with titanium alloys that have low thermal conductivity [13]. The recent development of eliminating both environmental hazards and machining cost has led to the usage of Minimum Quantity Lubrication (MQL). In this chapter, MQL is used to refer to a minuscule amount of lubricant spray (2 up to 50 mL/h) in a mist directly near tool-chip and/or tool-workpiece contact zone to provide the necessary lubricity, which is lacking in dry as well as wet machining. This technique is sometimes known as a near dry lubricating [20]. The use of MQL conducts the gasification of oil mist, which could absorb the generated heat in the cutting area. Another excellence of MQL is ecological friendly and more economy. It was reported that management of cutting fluid or coolant costs at least 16% of the product cost [21]. MQL and cryogenic are classified as green machining techniques.

The machining performance was investigated by [13] using a variety of cooling systems such as flood cooling, MQL, and cryogenic. The investigation was performed using solid end mill on titanium alloy, Ti6Al4V. At the same trials, the cutting force was analysed through the tool breakage detection. Nevertheless, they found that the cutting force for MQL hBN 70 + cryogenic is higher compared to MQL hBN 70 which are 1011 and 865 N, respectively.

Another observation conducted by [15], reported that cutting force increases when high cutting temperatures occur. Thus results in tool life reduction and poor surface quality. Increase in MQL flow rate can reduce the cutting force and tool wear up to a certain extent only. It was found that machining with cryogenic conditions resulted in excessive tool wear and microfracture and increased the cutting forces. Cutting force increased significantly as the Ti-alloy hardens with the application of the liquid nitrogen during the cutting. The cutting force for MQL rapeseed oil and MQL + cryogenic are the same about 1000 N at 47.7 m/min and the cutting force at 76.4 m/min for MQL + cryogenic slightly lower than MQL. A paper reviewed by [21] in 2017 that MQL + $SCCO_2$ is not adequate for cutting force reduction. More concern reported by [13], when conducted deep hole drilling of Ti6Al4V. In this process, the cutting tool can be suffered from strong adhesion due to the lack of lubrication, when only cryogenic cooling employed. He concludes that the lubrication method such as MQL should be added for a better result in deep axial depth-of-cut machining.

Nowadays, many researchers have shifted to MQL using vegetable cutting fluids. Ecological hazards, operator's health, and mineral oils rising cost are important concerns where that vegetable oils can compete with mineral oils. Significant disadvantages of mineral oils are toxic, non-biodegradable, open carbon cycle, and non-renewable. Vegetable oils have a higher capacity to absorb pressure thus have good lubricity properties. They also have a higher flash point, better boiling point, and as a result, there is less loss from misting. Coconut oil has been used for machining AISI 304. The result shows that coconut oil improved the surface finish, reduced tool wear compared to mineral oil [22].

It has been proved that flood cooling, though very useful at lower cutting speed, gets ineffective at higher speeds. This problem caused by the amount of heat generation at the tool–workpiece interface, which cannot be reached by the cutting fluids; hence the interface cannot be cooled [15, 23]. The result from green techniques of milling Ti6Al4V was the power consumption of MQL is lowest followed by dry, cryogenic, laser-assisted machining, and wet machining [21].

During thin-wall milling of titanium alloy Ti6Al4V, the low rigidity can cause vibration. The phenomenon of the vibration is known as a chatter. When the rigidity of the thin-walled workpiece is far lower than the machine-tool system in the direction perpendicular to the machined surface, dynamic milling model of the thinly walled workpiece can be regarded as a 1° freedom system, as shown in Fig. 1 [8, 14].

The dynamic equations for the tool–workpiece system can be obtained as:

$$m_x \ddot{x}_x(t) + \zeta_x \dot{x}_x(t) + k_x x_x = F_x(t) \tag{1}$$

where m_x, ζ_x, and k_x are the modal mass, damping, and stiffness of the tool-workpiece system in the X-direction. $F_x(t)$ is the cutting force in the x-direction. $x(t)$, $\ddot{x}(t)$ and $x(t)$ are the vibrational acceleration, vibrational speed, and vibrational displacement of the tool–workpiece system, respectively.

The equation of free vibrations for the system by neglecting the damping and the external force can be written as Eq. (2) [24].

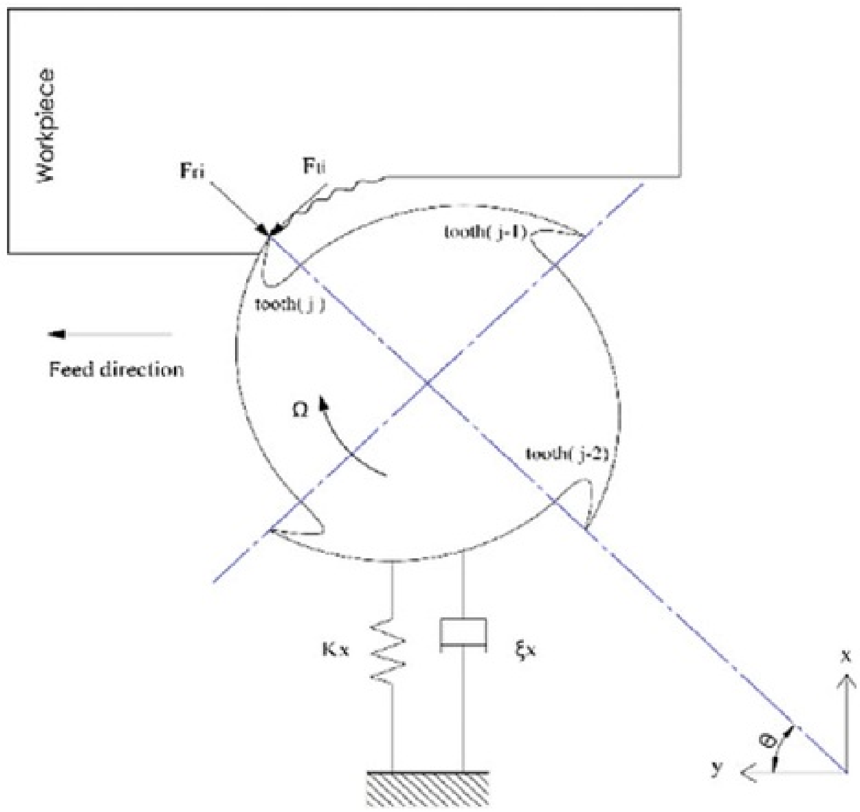


Fig. 1 Dynamic model of the thin-walled workpiece–tool system

$$M\ddot{x}(t) + Kx(t) = 0 \quad (2)$$

where M and K are the system mass, and stiffness matrices of size $(n \times n)$, respectively, and x is the n-dimensional column vector of generalised coordinates. Equation (1) for a single degree-of-freedom (SDOF) system can be written as Eq. (3).

$$m\ddot{x}(t) + kx(t) = 0 \quad (3)$$

If $x(t) = x_0 \sin(\omega t)$, where $\omega = 2\pi f$ is the rotational frequency, then Eq. (3) becomes $(-\omega^2 m + k)\, x_0 = 0$. The solution of $(-\omega^2 m + k) = 0$ gives the natural frequency of the SDOF systems (f_n), as shown Eq. (4).

$$f_n = \frac{\omega_n}{2\pi} = \frac{\omega}{2\pi} = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad (4)$$

Similarly, Eq. (2) can also be written as

$$\left(-\omega^2 M + K\right)x_0 = 0 \quad (5)$$

Or could be written as

$$(K - \lambda M) = 0 \tag{6}$$

Equation (6) represents the equation of the eigenvalues and eigenvectors, where $\lambda = \omega^2$ are a set of the eigenvalues, the $\lambda = [\lambda_1, \lambda_2, \ldots \lambda_n]$, and the corresponding eigenvector matrices are $\varphi = [\varphi_1, \varphi_2 \ldots \varphi_n]$ or called normal mode.

To identify the frequency content of milling force signals, Fourier transform is commonly used to transform from the time domain to the frequency domain. Since the signals from sensors are discrete, discrete Fourier transform (DFT) usually is used. DFT is given by [14, 25, 26].

$$F(k) = \sum_{n=0}^{N-1} F(n) \exp\left[\left(\frac{-j2\pi}{N}\right) kn\right], 0 \le k \le N - 1 \tag{7}$$

Based on the periodicity, symmetry, reducibility, and orthogonal of the exponential part of Eq. (7), FFT reduces the computational complexity of an N-point DFT to about $N \log_2 N$ arithmetic operations.

$$SF = \frac{n}{60} = \frac{1000v}{60\pi D} \tag{8}$$

[[[[The frequency spectrum is discrete to periodic signals; the amplitude spectrum appears at its variation frequency and harmonics. In milling process, the signal of cutting force is periodic, and its variation frequency is tooth passing frequency (TPF), so the amplitude spectrum of the cutting force shows peaks at TPF and its harmonics. However, the peak value of milling force will usually appear at spindle frequency (SF) and its harmonics for the mill run out. SF and TPF are defined as

$$\mathrm{TPF} = N.\mathrm{SF} = \frac{1000Nv}{60\pi D} \tag{9}$$

where n and v are the spindle speed (in revolutions per minute) and linear speed (in metres per minute), respectively, and D is the diameter of the mill. On TPF, the appearance of peaks at additional frequencies indicates the chatter. This well-known property of milling dynamics is often exploited for the detection of the chatter.]]]

2 Experimental Work

The cutting test was carried out on a high-speed milling centre MAHO DMC 835 V CNC 3-axis VMC, with an 18,000 maximum rpm spindle. Experiment set-up is shown in Fig. 2. The end mill tools used AlCrN-coated solid carbide with four cutting edges, the diameter of 10 mm and overhang length of tools is 30 mm.

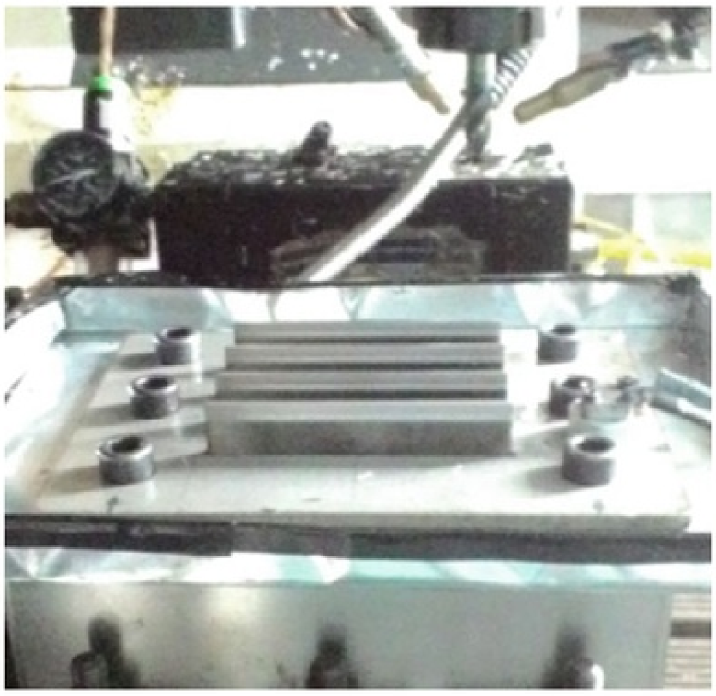


Fig. 2 Experimental set-up

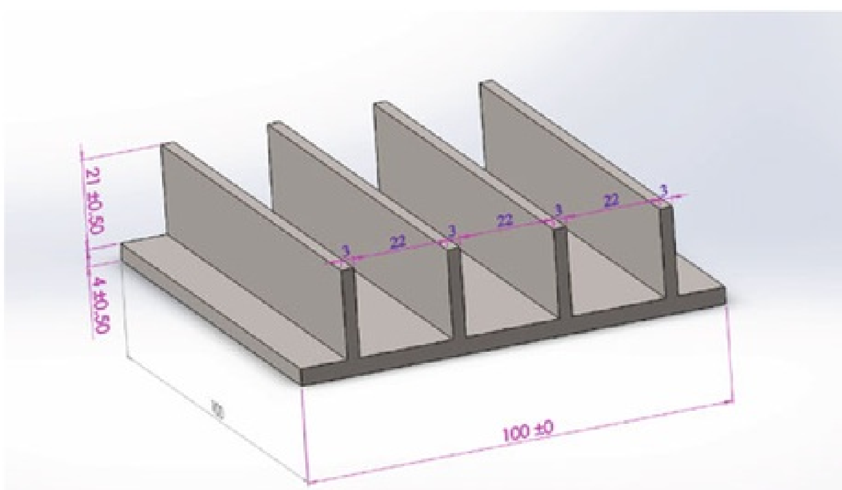


Fig. 3 Geometry and dimension (mm) of the workpiece thin-walled Ti6Al4V

The workpiece material was thin-wall titanium alloy Ti6Al4V (grade-5). Figure 3 shows the geometry and dimension of the thin-walled Ti6Al4V workpiece. The machining was done under MQL-cutting condition using coconut oils as the cutting fluids. The vibration of the workpiece was measured in the three directions of the tool feed (*x*-axis), perpendicular to the machined surface (*y*-axis) and the axial direction of the tool (*z*-axis). The workpiece vibration signal was monitored using accelerometer mounted on 35 mm in near the workpiece. The sampling rate in this experiment was set 20,000 s. The vibration signals magnified using a Daqcard

Table 1 Cutting process parameters

Trial numbers	Cutting speed (m/min)	Feed/tooth (mm/tooth)	Spindle frequency (Hz)	Radial DOC (mm)	Axial DOC (mm)
1.	64	0.063	135.76	0.32	7.07
2.	156.25	0.063	31.44	0.32	7.07
3.	100	0.025	212.12	0.32	7.07
4.	100	0.158	212.12	0.32	7.07
5.	100	0.063	212.12	0.32	7.07
6.	100	0.063	212.12	0.32	7.07
7.	100	0.063	212.12	0.32	7.07
8.	100	0.063	212.12	0.32	7.07
9.	100	0.063	212.12	0.32	7.07
10.	100	0.063	212.12	0.32	7.07

direct amplifier, and the analogue device was a National Instrument MX and collected by a data collection of the Dewesoft 7.0.6 software. The signals were analysed by MATLAB R2012a® software. To capture the surface quality, the Olympus STM6-LM was used. The thin wall was down milled with cutting process parameters are listed in Table 1.

3 Results and Discussion

3.1 Computation of Thin-Wall Natural Frequency and Vibration Analysis

The computation of thin-wall natural frequency is based on free vibrations with neglecting the damping. Natural frequency values are to compare with tooth passing frequency values of spindle speed in cutting parameters; it is done to avoid resonance or chatter in the machining process. The distribution of natural frequencies and mode shapes for SDOF is shown in Fig. 4. Based on Fig. 4 and Table 1, the frequencies of cutting parameters do not coincide with the natural frequency.

The mean values of workpiece acceleration at different cutting processes are shown in Fig. 5, in which x, y, and z represent the mean acceleration of x-direction, y-direction, and z-direction. It is observed that the increase in cutting speed and feed rate tends to increase acceleration in all the three directions. The acceleration value in y-direction or perpendicular to the machined surface is higher than the other directions.

The frequency and surface topography will be used to analyse further vibration analysis on thin wall. Figure 6 section first (time domain vs. acceleration) is shown

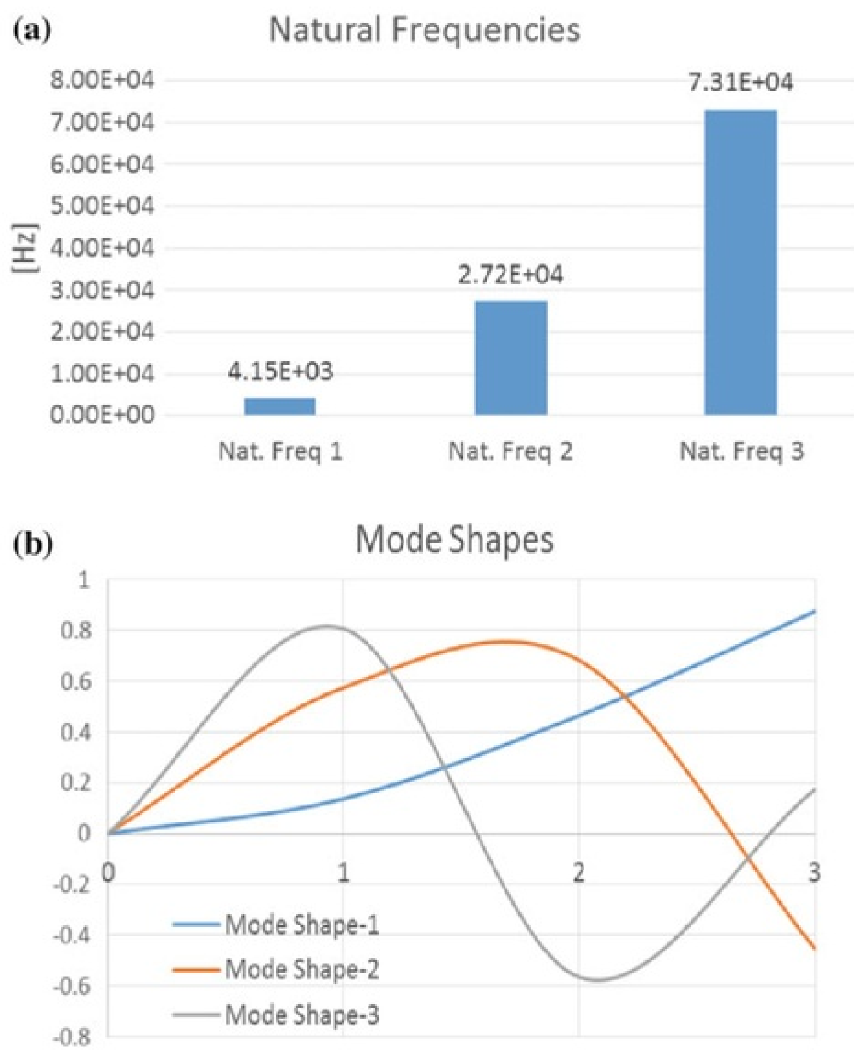


Fig. 4 **a** Natural frequency. **b** Mode shapes of the thin wall

the raw signals of the vibration. The cutting process is divided into three states—entry cutting, machining cutting, and exit cutting. The data during machining state is used to analyse the influences cutting process towards vibration. To verify the cutting process, whether unstable machining (chatters) occur, the vibration *y*-direction was analysed using FFT. The fast fourier transform spectrum is shown in Fig. 6.

It is shown that the peak values of milling vibration are more significant when the cutting speeds are 156.25 m/min, feed rate 0.025 and 0.158 mm/tooth. When cutting speed is 100 m/min, its frequency spectra distribution is stable. In order to further analyse stability machining (chatter), no chatter appears on all machining. Dominant vibration or maximum point's peak value occurs at 4000, 4503, 5333, and 6000 Hz, but it causes no chatter.

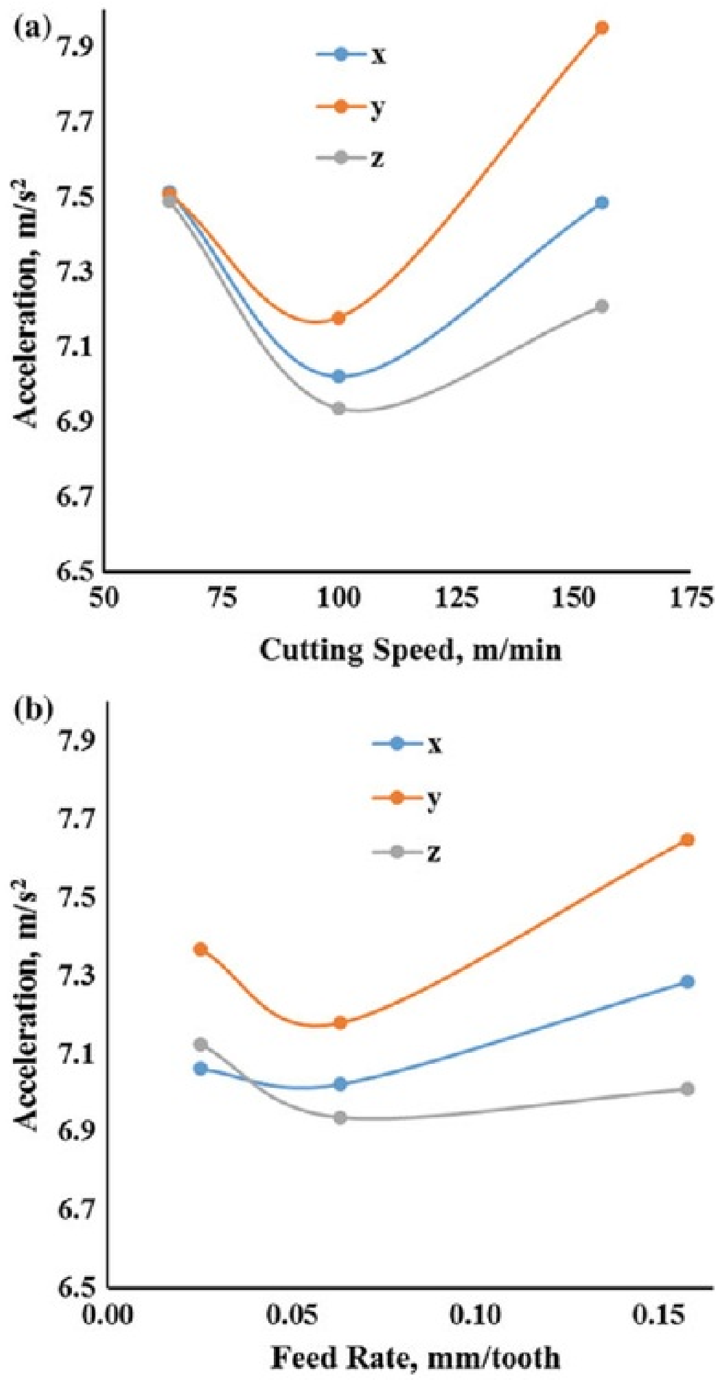
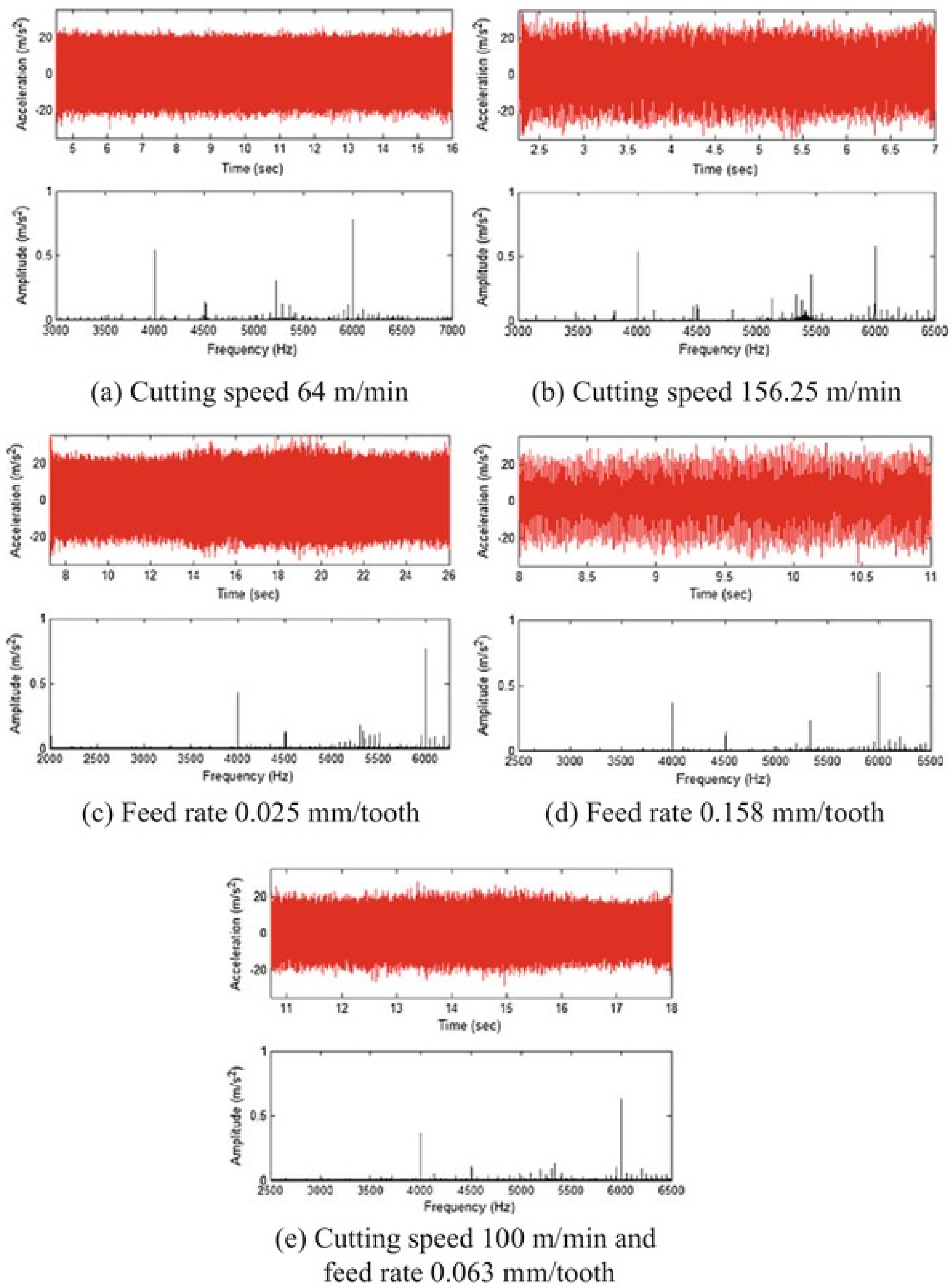


Fig. 5 Vibration acceleration on, **a** cutting speed, **b** feed rate variation

3.2 *Surface Quality*

However, on the surface topography as shown in Fig. 7, the surface is poorer at a maximum cutting speed and maximum feed rate. Based on these results, it can be proven that the experiments were in good agreement and the maximum vibration appears far away from the natural frequency.



(a) Cutting speed 64 m/min

(b) Cutting speed 156.25 m/min

(c) Feed rate 0.025 mm/tooth

(d) Feed rate 0.158 mm/tooth

(e) Cutting speed 100 m/min and feed rate 0.063 mm/tooth

Fig. 6 Time domain and FFT output during machining at cutting speed and feed rate variation

The surface topography has shown small influence due to vibration on the surface texture. This phenomenon can be proven when the surface roughness values were measured using surface roughness tester Accretech Handy-Surf type E35A/E. The influence of cutting speed and feed rate is shown in Fig. 8a, b.

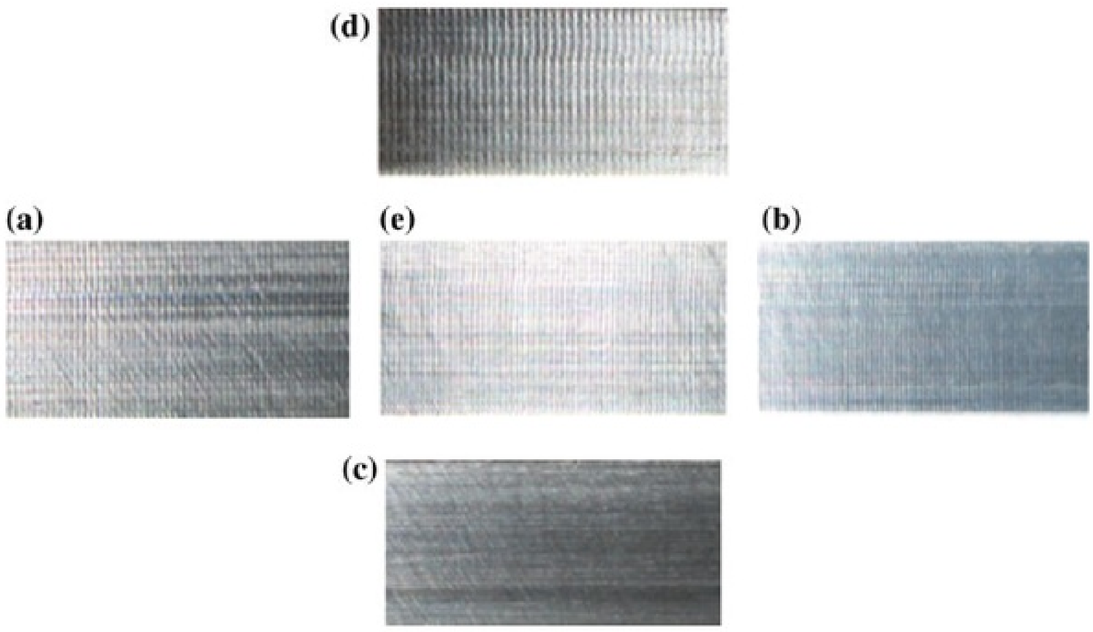


Fig. 7 Surface photographs of the workpiece at cutting speed and feed rate variation. **a** Vc = 64 m/min, **b** Vc =156.25 m/min, **c** fz = 0.025 mm/tooth, **d** fz = 0.158 mm/tooth, **e** Vc =100 m/min and fz = 0.063 mm/tooth

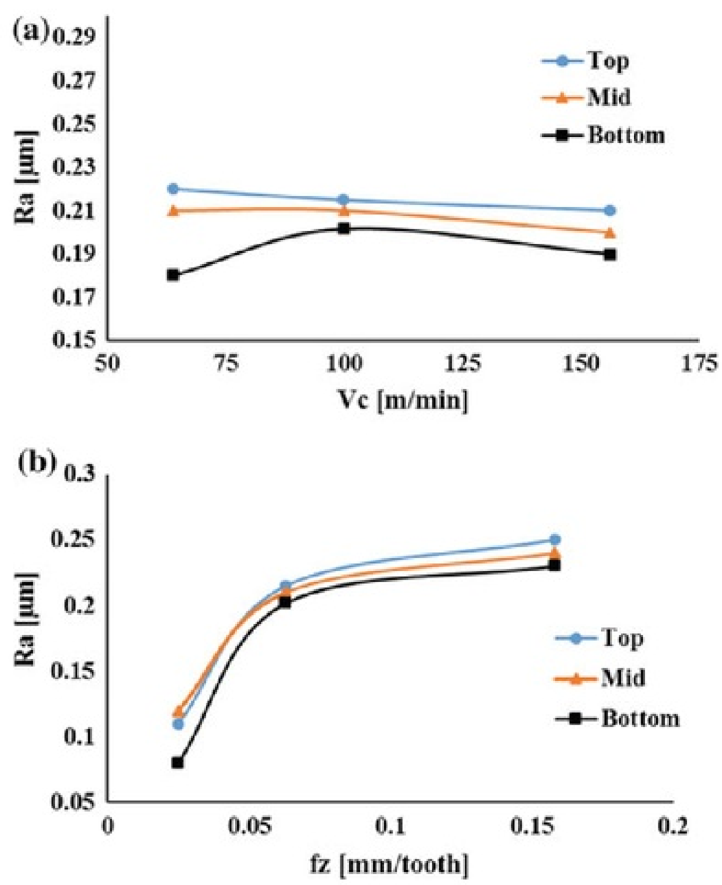


Fig. 8 Influence of cutting speed, **a** and feed rate, **b** on surface quality at several positions of thin-wall Ti6Al4V

From Fig. 8a, it is apparent that increasing cutting speed generally affected on decreasing surface roughness values, hence yield in better surface quality. On the other hand, increasing the feed rate yields in poorer surface quality as shown in Fig. 8b.

This phenomenon is agreeing with the basic theory propagation of surface roughness, which also proven in [27] during hard turning on AISI D2 steel. Solely at the bottom of the thin wall, the surface roughness is increased with the rise of cutting speed. From Fig. 8, it is also to recognise that the surface roughness values decrease from the top to the bottom of the thin wall. This could be caused by the deflection on the top of the thin wall is higher than the bottom. Thus, the surface deterioration is more influenced on the top of the thin wall.

4 Membrane Technology

4.1 Potential and Handling of Membrane Technology

It is known that conventional cutting fluid is hazardous, but reducing the amount of cutting fluid to control environmental hazard leads to compromising performance measures. In this case, operations with minimum quantity lubrication (MQL) is one of the strategies that can offer technological that associated environmental concerns and economic advantages over the traditional fluid application. Under MQL, microdroplets of sustainable lubricants are supplied in the machining zone. The prevailing trend of many researchers in machining processes, vegetable oil, has been selected as cutting fluid based on their ability to influence performance and characteristics such as biodegradability, oxidation stability, and storage stability.

Vegetable oils possess excellent lubrication properties, resistance to corrosion, and high flash and boiling points.

Storage and disposal of exhausted cutting fluid have always been challenging for the machining industry.

Removing the chips in the wasted cutting fluid is the first step to treat the waste cutting fluid [28]. In this study, oily water emulsion, similar as wasted cutting fluid, are the primary pollutants emitted into the water by manufacture operation and tend to have significant pollution problem because oilfield produced water has distinctive characteristics due to organic and inorganic matter. Fatty alcohols and synthetic hydrocarbons which include the waste cutting fluid are initiated hazardous materials. Some treatments of oily wastewater have been studied namely, chemical emulsification, pH, gravity settling, centrifugal settling, filter coalesce, heating treatment, electrostatic coalesce, and membrane filtration. The unit operations and processes used for the removal of significant constituents found in wastewater are tabulated in Table 2.

Table 2 Unit operations and processes used to removed constituents found in wastewater

Constituents	Appropriate treatment technologies
Suspended solids	Screening, grit removal, sedimentation, flotation, chemical precipitation, surface filtration
Biodegradable organics	Aerobic suspended growth variations, Aerobic attached growth variations, physical–chemical systems, chemical oxidation, advanced oxidation, membrane filtration
Refractory organics	Carbon adsorption, chemical oxidation, ion exchange, breakpoint chlorination, membrane filtration
Heavy metals	Membrane filtration, evaporation, electrodialysis, chemical precipitation, ion exchange
Fat, oil, and grease	Coagulation/flocculation/floatation, membrane ultrafiltration
Colloidal and dissolved solids	Membrane filtration, chemical treatment, carbon adsorption, ion exchange

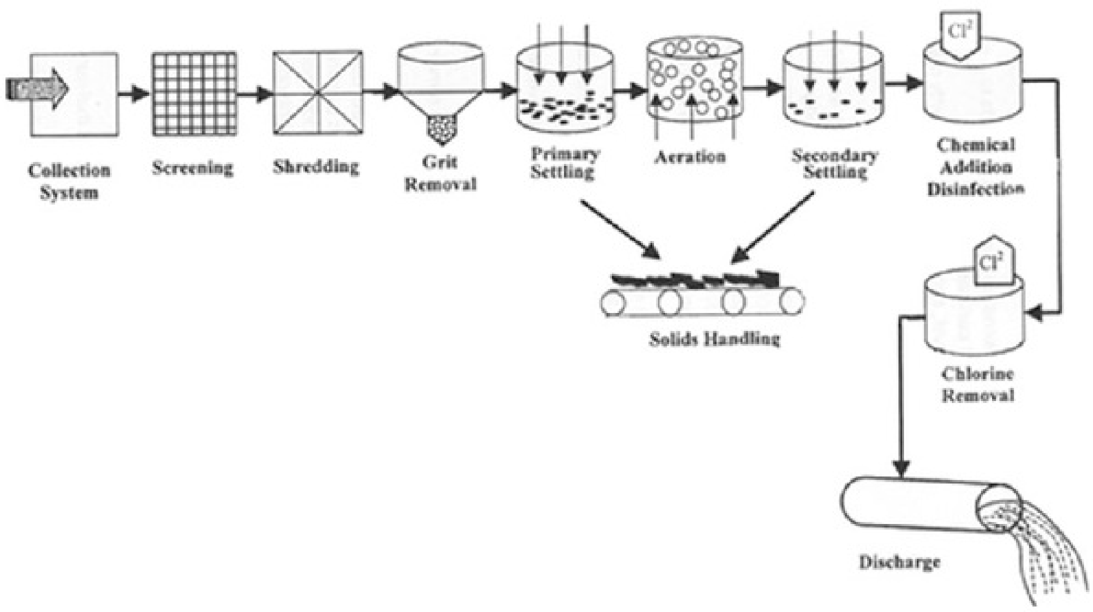


Fig. 9 Mechanism of wastewater treatment

The suspended solids and other constituents that are difficult to remove are being treated by improved and new technologies. The unit operation for wastewater treatment is shown in Fig. 9, while the terminology of wastewater constituent removal using a membrane is shown in Fig. 10.

The performance evaluation of various membrane materials was reported by [29]. They evaluated the suitable membrane materials for the coolant wastewater treatment and the effect of nanoparticles additives on the membrane morphology.

They concluded that the application of PVDF membrane in the metal industry for long-term performance could be an alternative solution regarding the purpose of nanoparticles in the membrane to minimise fouling and prolong the membrane

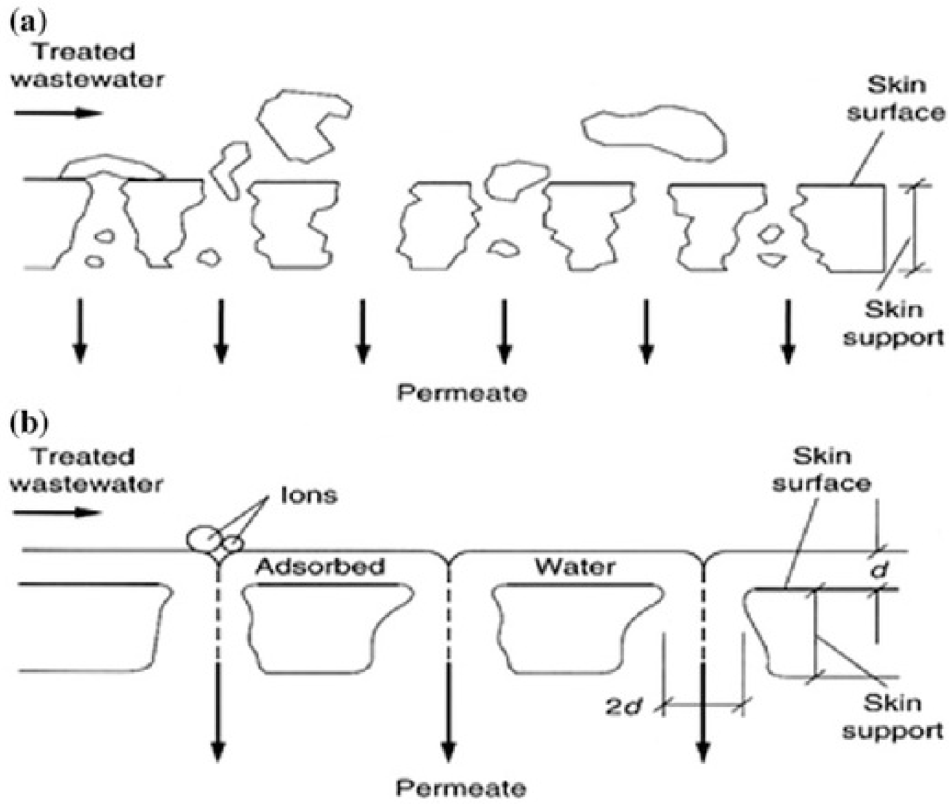


Fig. 10 Rejection of ions by adsorbed water layer in waste water treatment by membrane technology

lifetime that affects directly to the enhancement of the efficiency of the treatment process. Heterogeneity of coolant effluent has been reported by some researchers because it is made by nature and effect of fouling that was harder to control and forecast. The fouling phenomenon of the membrane is one of the drawbacks in membrane technology that cannot be prevented but can be minimised. Related to the fouling phenomenon, hydrophilicity characteristics plays also important role in oily wastewater filtration. Hydrophilicity contributes to the formation of a thin, protective water film on the membrane surface that increases the water removal from wastewater cutting fluid. On the otherhand, hydrophobicity tends to repel and not absorb water. It has been reported that hydrophilicity membranes have more advantages concerning fouling than hydrophobic membranes [29].

4.2 PVDF Membrane for Mitigation of Wasted Cutting Fluids

As known, membrane separations have been significantly developed over the last three decades and are becoming an essential place in wastewater treatment. The membrane technology has emerged as an alternative to the conventional physical–chemical treatment process and also decreased the environmental pollution significantly. Membrane filtration system involves the passage a wastewater through the thin membrane for removing particulate materials, organic matters, nutrients, and dissolved substances, which cannot be removed by conventional treatment processes. Membrane processes include microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), reverse osmosis (RO), and electrodialysis (ED). The microfiltration and ultrafiltration membranes are used for filtrating the secondary effluent in depth and surface filtration. Meanwhile, nanofiltration, reverse osmosis, and electrodialysis systems are used for removing the dissolved solids. They also have high oil removal efficiency, low energy cost and compact design compared with traditional treatment. Many studies of membrane separation for oily wastewater treatment have been reported, particularly in microfiltration (MF) and ultrafiltration (UF). The performance of hydrophobic polyvinylidene fluoride for oily wastewater filtration can be characterised according to their permeability, rejection ability, and fouling resistance [30]. More specifically, such performance can be compromised due to pore clogging via oil particle, preferential adsorption of oil which can result in fouling as well as the formation of cake layers on the membrane surface.

Regarding the application of membrane in wasted cutting fluids treatment, PVDF membrane achieved the significant result to remove the contaminant and also remove the colour component. Part of colour pigment which affected by vaporisation could be remained by adsorption on suitable bleaching earth. The remaining colour components are the thermally degraded during deodorisation at high temperature (150 °C) for 100 min.

Part of the colour pigments are physically adsorbed by bleaching earth, and other components are chemically bound to bleaching clay via covalent or ionic bonds [31]. Decomposes peroxide in alkoxyl and alkyl radicals occur as first step in oxidation pathway. Second step, acid activation enhances the adsorptive power due to an increasing negative surface area of the membrane. Based on these results, it can be concluded that modified PVDF membrane with the negative charged surface is the better solution in order to treat the wasted cutting fluid.

4.3 Experimental Set-up of PVDF Membrane Technology

The coolant wastewater was produced while the milling of thin-wall Ti6Al4V using coconut oils as cutting fluids under MQL systems. After finished the experiment, the exhausted cutting fluid was collected in a bottle. For this experimental purpose, it is must to prepare a synthetic coolant wastewater according to a collected sample of MQL-exhausted cutting fluids, which was collected in the previous experiments. The prepared synthetic coolant wastewater is to be used as the feed solution in ultrafiltration experiments [32].

Table 3 Properties of PVDF membrane

Parameter of the membrane	Type/value
Membrane material	PVDF/SiO_2
Membrane configuration	Hollow fibre
Inner diameter (mm)	0.6
Outer diameter (mm)	1.2
Membrane area (dm^2)	10.48
Pore size (nm)	35.2

The submerged membrane separation system used in this experiment consists of a feed reservoir up to 14 l volume, hollow fibre bundles, a peristaltic pump, a permeate flow metre, and a permeate collector. The boundary conditions of the filtration experiments are as follows: vacuum on the permeate side 0.5 bar abs, room temperature.

The membrane was produced using a peristaltic pump (Master flex model 7553–79, Cole Palmer) with the water permeate being withdrawn from the open end of fibres. In order to let the water permeate from outside to the inside of the hollow fibre, the transmembrane pressure (TMP) was maintained at a constant pressure of 0.5 bar. The turbulent flow was created using the continuous aeration so that the cake layer thickness and the average particle size could be reduced.

The properties of the membrane used in this experiments are given in Table 3.

In these experiments, the hollow fibre membranes were immersed in the feed reservoir. The withdrawal of permeate through the fibre was generated using the employment of vacuum on the outlet of the fibre lumen [33–35].

To characterise the oily machining wastewater, several substances were taken into account as measured parameters, namely oil and grease, chemical oxygen demand (COD), total organic carbon (TOC), sulphide, and total suspended solids [36].

4.4 PVDF Membrane Experiments Results

The removal of organic wastes from oily wastewater has been proven successfully using developed PVDF membrane technology and its application in coolant wastewater filtration. In this device, hollow fibre membranes are directly immersed in the feed reservoir with the withdrawal of permeate through the fibres in vacuum pressure application on the fibre lumen outlet of the membrane. As known, coolant wastewater was characterised by the presence of chemical oxygen demand (COD), total organic carbon (TOC), and suspended solids (TSS). After coolant wastewater filtrating using PVDF hollow fibre membrane with factors such as mixed liquor suspended solids, the concentration of coolant wastewater, pH and hydraulic retention time, the results of the study were achieved in the value of COD 555 mg/L, TOC of 29.1 mg/L, and suspended solids of 20 mg/L. These values were achieved entirely using modified PVDF hollow fibre membrane with SiO_2 additives that affected as modifier area, highly miscible, fine suspension ability in aqueous solution and relatively environmentally inert. PVDF/SiO_2 has been found to be a promising modifier to improve the permeability and selectivity of PVDF membrane [32].

5 Conclusions and Future Directions

In this study, dynamic behaviour during end milling thin wall of Ti6Al4V is verified. The results found are as follows:

1. It was found that the natural frequencies occurred are 4154.5, 27,203, 73,089 Hz for the first, second, and the third, respectively.
2. The dominant vibration or maximum point's peak value occurs at 4000, 4503 and 5333, and 6000 Hz.
3. The vibration value in *y*-direction or perpendicular to the machined surface is higher than the *x*-direction and *z*-direction.
4. The value of acceleration in three directions increased significantly with the increase of cutting speed and feed rate.
5. The surface quality is better when the cutting speed increased. In contrary, the surface quality becomes worst when the feed rate rise.
6. The results of the study were achieved in the value of COD 555 mg/L, TOC of 29.1 mg/L, and suspended solids of 20 mg/L. These values were achieved entirely using modified PVDF hollow fibre membrane with SiO_2.
7. PVDF/SiO_2 has been found to be a promising modifier to improve the permeability and selectivity of PVDF membrane.

The proposed future work in this field is to observe the opportunity of combining vegetable oils in MQL, cryogenic, and air-cooled systems.

In order to mitigate the hazardous effect of the wasted cutting fluids, the PVDF membrane offers an excellent solution. Thus, the green machining through coconut oils as cutting fluids in MQL system has been proven the optimum cutting condition for the aerospace materials such as titanium alloy.

Through the optimum selection of a cutting condition, the occurred vibration in machining of Ti6Al4V can be controlled in the acceptable zone. Thus resulted in adequate surface quality.

The higher cutting speed should be investigated in the future to find higher optimum cutting condition, which suitable for the machining of titanium

In the handling of wasted cutting fluids, it is essential to explore the opportunity of other types of the membrane in filtering the wasted cutting fluids to foster the environmentally friendly machining process, especially for aerospace materials.

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