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Energy consumption modeling of ultra-precision machining and the experimental validation

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Abstract

Enormous precision products are fabricated by precision machining technologies nowadays. Ultra-precision diamond cutting, which is one of the most applied machining ways in ultra-precision machining (UPM), figures the importance of precision manufacturing nowadays. However, the existing energy consumption models currently used for UPM are applied to traditional machining processes, of which the energy component of material removal process only considers the assigned material removal volume in UPM. Nevertheless, the material recovery effect is dominant in material removal processes in UPM, which it significantly reduces the assigned material removal volume. This study therefore proposes a modified energy consumption model for the UPM by adding the material recovery factor. The representative machining technology of UPM, ultra-precision diamond cutting, is used for the case study in this study. The experimental results showed that the accuracy percentage of proposed energy component regarding to material removal process increased to 83.39%. Also, the specific energy consumption obtained by the proposed approach increased up to 11.2 times of that in the traditional approach. This study demonstrates the noteworthiness of the material recovery effect on the energy consumption of UPM, providing a valuable insight for arranging realistic environmental plans with references in precision manufacturing industries.

Keywords: Ultra-precision machining; Energy consumption model; Specific energy consumption; Material recovery; Ultra-precision diamond cutting

1. Introduction

The issues of energy consumption in different industries are highly related to economics and sustainable developments of cities. Increases in energy demands due to population growths and fast technology developments cause environmental problems especially global warming and climate change, health impacts from pollutants, and water contaminations [1–4]. Therefore, the full attentions of energy consumption activities in manufacturing have been specifically focused nowadays, which the energy consumptions from manufacturing sectors exert considerable impacts on the sustainable productions [5,6]. According to the record from U.S Energy Information administration [7], the energy consumption of manufacturing sectors is over two-thirds of total energy used in the industrial sector, which is approximately equal to 22.2 quadrillion kJ per year in the U.S. alone. For the high proportion of energy usage within the manufacturing sector, the energy consumption in manufacturing takes a crucial role in sustainable development of industries. Thus, it is essential to pursue a detail investigation on the energy consumption model in manufacturing. By understanding the energy components involved in fabrication processes, the meticulous amount of consumed energy of particular manufacturing processes could be indispensably obtained, which is of great consequences to improve the energy efficiency in manufacturing.

The demand for high precision products has been increased substantially in recent years [8], and ultra-precision machining (UPM) is one of the machining technologies for fabricating such precise products for the optical, automotive and medical fields. UPM is mainly applied to generate excellent quality and functional parts with high accuracy [9]. The greater awareness of UPM in the manufacturing sector arising from the demands of precision products, has led to extensive researches into the energy consumption involving into it. Under exploring the energy consumption model of mechanical micromachining for fabricating micro-devices, Liow [10] concluded that the difference of energy consumption between conventional and micro machining was over 800 times. Yoon et al. [11] investigated the energy consumption involved in the material removal process of micro machining and, found out that the energy consumption and the manufacturing cost were highly related to the process parameters, and a high material removal rate would reduce the energy consumption but increase the machining cost. Balogun and Mativenga [12] obtained the energy demands of micromachining while considering of the mechanistic forces, and empirically established the specific electrical energy through cutting tests. According to literatures, the material swelling effect in UPM is demonstrated conclusively in ultra-precision raster milling and ultra-precision diamond cutting [13]. Although the cutting mechanisms of these two machining technologies are various, recovered materials arising from the material swelling effect on the manufactured surface by these two technologies are particularly significant. Researchers investigated extensively about the energy consumption model of these two typical approaches in UPM.

1.1 Material recovery effect in ultra-precision machining

Unlike conventional machining, dominant sliding along the flank face of tool on the machined surface are involved in UPM processes especially diamond cutting and milling, which they cause a unique material response from the machined surface after UPM – material recovery. Material recovery is due to diamond tool plowing induced by a large tool negative rake angle, whereby the tool rubs on the machined surface in the UPM processes. In UPM, material recovery basically occurs at the tool nose cut surface [14]. Figure 1 demonstrates the surface profiles of ideal and actual machined surfaces affected by the material recovering effect. During UPM, machined materials on the surface flow laterally from the tool edge because of a high-pressure exertion from the tool to the machined surface. The flowed materials become a viscous fluid caused by high cutting temperature generated in continuous cutting, consequently, the metal fluid stays at the machined surface and solidifies with the temperature decrease [13]. Ultimately, the machined surface expands because of the thermal expansion effect, leading to a ragged surface on the workpiece and decreasing the material removal volume [15]. Actually, the energy components related to the material removal volume is one of the important elements in the energy consumption model of machining processes. Because of the recovered materials, the practical material removal volume in UPM is significantly different from the assigned one. With this reason, the cutting energy involved in UPM is believed to considerably deviate from that of conventional machining. It is therefore critical to determine the related energy dissipation precisely, which is unique to UPM.

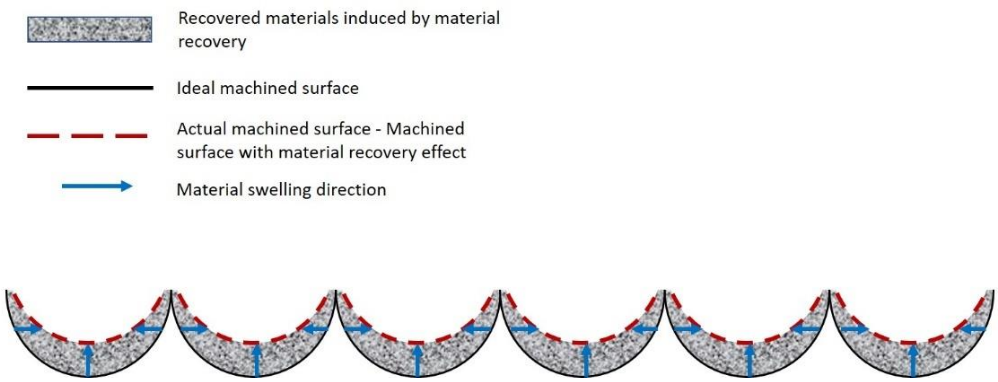


Figure 1. Material recovery effect in UPM

In response to the unique material response in UPM, researchers have proposed various energy consumption models, including different factors of the distinctive material recovery effect. Lucca et al. [16] investigated the overall energy balance for micromachining with low depth of cut and they discovered that material elastic recovery in UPM significantly affected the mechanical energy dissipation in micromachining. Lucca [17] conducted experimental investigations to understand the effect of the plowing process induced by material recovery on the dissipation of mechanical energy in micro-cutting and showed that the plowing process was the main factor in the energy dissipation of micro-cutting. Balogun et al. [18] evaluated the specific ploughing energy in the micro-milling process and proposed an optimized model, which the model included the ploughing effect caused by material recovery. Many researches indicate that the material recovery effect performs a decisive role in the energy consumption in UPM.

In UPM, the level of precision for its fabricated products is demanding and restrictive. Although the material recovery effect is not significant in conventional machining, it strongly exerts in UPM and influences the surface quality of UPM fabricated products [19]. According to the definition of UPM by industries and scholars, UPM defines as the reachable level of form accuracy in the order of less 0.2μm and surface roughness in the order of less 10nm [20]. The resolution and repeatability of the machining facilities is less 10 nm [9]. The machining accuracy for UPM is 1000 times in surface roughness and 100 times in form accuracy in comparison to that of conventional machining. Therefore, only a slight level of material recovery on the machined surface would definitely cause unacceptance of final products in the market. However, wrong determinations of energy consumption in UPM usually happen in industries because of under evaluations of material recovery effect which it still cannot be embraced up to now. Industries and researchers investigated the approaches for minimizing the material recovery effect in order to maintain the precise product quality, hence, extra efforts are always paid for it and therefore the environmental strategies for planning energy saving in UPM are much different from traditional machining technologies. With the consideration of material recovery effect on the energy consumption model of UPM, much more accurate and realistic energy saving plans for UPM processes could be developed and executed. Nowadays, there are many high technological products made by the UPM approaches, from industrial uses to commercial uses; the typical examples for industrial products are mold inserts while commercial products are freeform optical glass, automobile components and electronic diodes. The demands for those high technological products would predictably increase because of the society needs in the future. Starting from 2006, the precision machining industry has created 9,791,795,000 US dollar of product shipments, and the business value is about 9.8 billion US dollar. According to the annual survey of Manufacturers Value of Product Shipments, it demonstrated that the precision products relating to automotive value at 2,368,495,000 US dollar in import and export shipments, which is 24% of the industry's total. The enormous portion of precision products within the industries reveals an importance of UPM technique to the manufacturing sector. Therefore, the energy consumption issue relating to the fabricating activities of UPM is cogently expressed, because of the huge impacts from the manufacturing sector to the society.

An inappropriate determination of energy consumption of UPM would cause inattentive focuses on the effect of material recovery on decisions of environmental strategies in UPM. For such big proportion value in the manufacturing sector, a failure of executing viable environmental strategies for fabricating activities of UPM would consequently raises another serious problem relating to the environmental issue. Therefore, in this study, a modified energy consumption model with the consideration of material recovery factor is established for showing the accurate energy consumption boosted from UPM processes, it aims to demonstrate an importance of the material recovery effect on the energy consumption of UPM, providing the new insight to micro-manufacturing sector to plan for effective environmental strategies.

1.2 Rationale of proposed new energy consumption for ultra-precision machining

Generally, the symbolic machining technologies of UPM are still ultra-precision diamond turning (UPDT) [24], and also ultra-precision raster milling, and they are the most used technologies in UPM currently. For both of these machining technologies, the material recovery effect is the dominant factor, which causes ragged surfaces on the workpiece generated by UPM, and the recovered material volumes occupy a large proportion of assigned removal material volume. In particular, when the machined materials consist of material properties of low thermal conductivity and low elastic modulus, the material recovery effect in UPM is sharply intensified, which that phenomenon has been reported and supported by the literature. Yip and To [13] reported that the recovered material volume in diamond cutting of titanium alloys was exceptionally large in comparison to the assigned material removal volume. The volume of recovered materials in diamond cutting of titanium alloys counted for 36.7% and 28.2% in the bottom and side areas of machined surface respectively, which occupied almost one third of assigned material removal volume. It is clear from the foregoing that the material recovery effect in UPM creates tremendous impacts on the material removal volume and thus the material removal rate. With the influences on the material removal rate and material removal volume, the energy consumption model and energy efficiency of UPM are believed to be different from the traditional and existing reported models. Up to now, the reported energy consumption models for machining in literatures mainly consist of the energy components with considerations of assigned material removal rate and volume [22]. The material recovery effect does not only contribute to the energy component caused by the ploughing motion as literatures reported, it also pitches in the energy component related to the material removal rate and the material removal volume in the existing models. This study therefore proposes a new energy consumption model including the material recovery factor into the energy components, which is validated by the case study of diamond cutting of titanium alloys in this article.

2. Theory

2.1 Material recovery effect in UPM

The employments of ultra-precision machining technology lean on the efforts of machine tools such as single-crystal diamond tools and precise machine components including air bearings, air slides, granite beds mounted by air and precise position-control technology [23]. In the late 1970s, UPM was employed to respond the demands of the computer, electronics and defense industries for manufacturing high precision parts [24]. In the recent years, multi-axis controlled UPM has been widely applied to satisfy the rising demands for freeform surface products. And, researchers generally describe diamond turning or cutting as UPM. Actually, the material recovery effects are amply reported to happen in the two representative UPM technologies in literatures, they are ultra-precision raster milling and ultra-precision diamond cutting, which these two machining technologies are the most common types in UPM and raised lots of attentions from researchers. In ultra-precision raster milling and ultra-precision diamond cutting, burnishing and recovery generally happen on the machined surface during fabricating the tool-edge cut surface. Figures 2 and 3 show the schematic diagrams of material recovery in ultra-precision diamond cutting and ultra-precision raster milling respectively. During the UPM processes, the phenomenon of elastic recovery on the machined surface occurs when the tool cuts the surface. For ultra-precision raster milling, materials are removed by discontinuous contacts establishing between a single point diamond tool mounted on the spindle and a workpiece fixed on the table. The diamond tool is forced to rotate because of operation of air spindle, and it moves linearly along Y axis and X axis while the workpiece moves linearly along Z-axis, they interact with each other to generate the desired machined surface. For ultra-precision diamond cutting, the diamond tool directly contacts with the workpiece. The workpiece is mounted into the fixture attaching to the spindle, the fast-rotational motion of workpiece interacting with the linearly moved diamond tool generated a precise material removal process. Because of high pressure acting on the machined surface by the cutting tool, the recovered materials normally locate at side and bottom positions of the cut surface, named as side recovery and deep recovery respectively [13]. Side recovered materials are generated by the side flow materials when the tool edge exerts high pressure and load on the machined materials. Those side flow materials become viscous fluid under continuous cutting, and finally the metal fluid staying at the two sides of the tool edge solidifies and expands with the temperature decrease. Simultaneously, deep recovery is an increase in material volume at the bottom position of machined surface after the UPM processes. Both the recovered materials at the side and bottom positions contribute to a significant decrease in assigned material removal volume and therefore the energy components regarding to material removal in the energy consumption and specific energy consumption are affected.

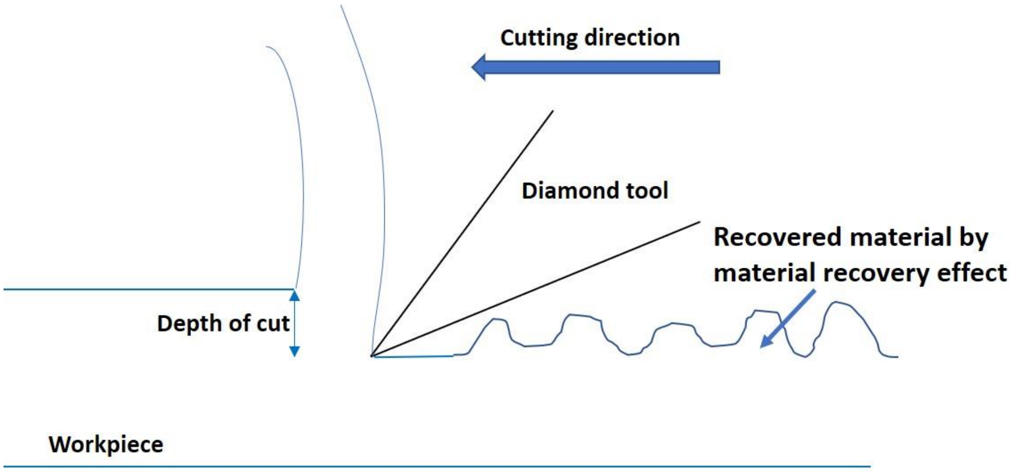


Figure 2. Schematic diagram of material recovery in diamond cutting in UPM

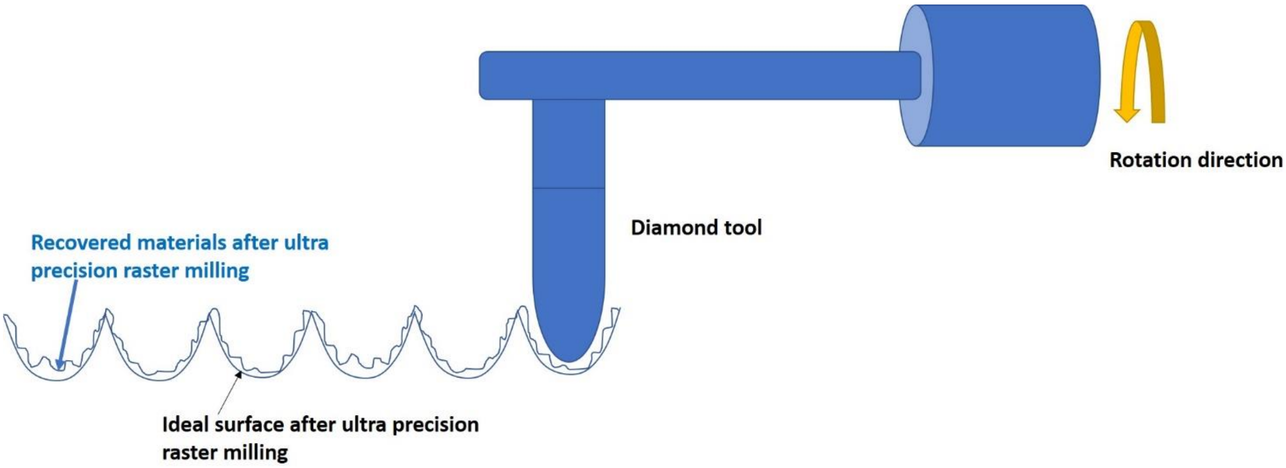


Figure 3. Schematic diagram of material recovery in raster milling UPM

2.2 Existing energy consumption models for machining

Researchers have investigated the specific cutting energy of machining processes and established energy consumption models previously. Lin et al. [25] provided a reliable energy consumption model for different machining conditions for milling machines, the accuracy of the developed model increased lots. Li and Kara [26] established an empirical model focusing on the power of the machine tool under different cutting conditions to offer an energy consumption model for assigned process parameters. Draganescu et al. [27] developed statistic modelling emphasizing the machine tool efficiency, which the machine tool efficiency, specific consumed energy and consumed energy had been obtained as functions of different machining parameters. Diaz et al.[28] modified the energy consumption model for milling machine tools concentrating on the power demand under cutting low carbon steel with different material removal rates. Researchers have developed the theoretical and initial empirical models; they have shown that the material removal rate is the conclusive factor of unit process energy consumption for machining processes. Industries and researchers expressively agree with the detail mentioned above, the energy consumption models in manufacturing are highly related to the material removal rate and thus material removal volume. The material removal rate does not only interrelate to the machinability of the workpiece and machining capacity with limited resources [29], it also relates to the optimum machining parameters for the best energy usage.

The works from Lin et al. [25], Li and Kara [26], Draganescu et al. [27] and Diaz et al.[28] derived specific energy consumption and energy consumption models including the machining parameters and material removal rate only. Although the models are in high accuracy and allow manufacturers to obtain the model coefficients quickly, these models mainly considered the machine tool and the machining parameters in the energy consumption model without providing the insight on material properties of workpiece. Therefore, it is valuable that we develop a model including the material factor especially the material recovery effect, which is dominant in UPM. The energy consumption models are needed to modify to reflect the importance of the material recovery effect in the practical UPM processes.

3. The modified energy consumption model in ultra-precision machining

In a machining process, energy is needed for the operation of machining equipment (Basic energy), the process of value adding activity (Ready State), and finally the generation of the source of machining samples. For ultra-precision diamond cutting, the total energy consumption E per single turning pass includes several parts, which are machine set up energy E_1, operating energy for machine E_2, tool interchange energy E_3, normalized cutting edge energy from the tool fabrication E_4 and material removal energy for producing a workpiece E_5 [30,31] is

$$E = E_1 + E_2 + E_3 + E_4 + E_5 \quad (1)$$

, where

$$E_1 = P_0 t_1 \quad (2)$$

$$E_2 = P_0 t \quad (3)$$

$$E_3 = P_0 t_2 \left({}^{t}/_{T_L} \right) \quad (4)$$

$$E_4 = y_E \left({}^{t}/_{T_L} \right) \quad (5)$$

P_0 is the power of machine for the machining process, t is cutting time for one turning cycle, t_1 is machine setup time, t_2 is tool interchange time, T_L is tool life and y_E is energy per cutting edge. For the ultra- precision milling case, the overall energy consumption is composed of few parts, they are main machine functional modules, the machine stand-by and the energy consumed for cutting materials [32], hence, equation (1) is universal for both ultra-precision diamond cutting and ultra-precision raster milling, which they are the most employed machining technologies affected by the material recovery effect in UPM. Focusing on the energy component compiled with the material removal element, which is E_5

$$E_5 = k\dot{v}t \quad (6)$$

where $\dot{v}$ is the material removal rate per one cycle turning pass and k is the specific cutting energy per volume of material. Through replacing the equations by the material removal volume in the machining process, E become

$$E = P_0 t + P_0 t_1 + P_0 t_2 \left({}^{t}/_{T_L}\right) + y_E \left({}^{t}/_{T_L}\right) + k\dot{v}t \quad (7)$$

$$E_5 = k\frac{Vol}{v}t \quad (8)$$

where Vol is the material removal volume per cutting cycle and v is the cutting speed. As the material recovery effect is dominant in a UPM process, the energy components for the material removal rate in the energy models reported in the literature are required to add the factor of material recovery.

Therefore, equation (8) is revised to:

$$E_5' = k\frac{Vol + Vol_{mr}}{v}t \quad (9)$$

where E'_5 is the modified energy components for the material removal energy in UPM. Vol_{mr} is the recovered material volume induced by the material recovery effect in UPM. Actually, E'_5 should include the energy component of “material removal energy for producing a workpiece” E_p and “material removal energy for generating recovered materials induced by the material recovery effect” E_{mr}.

$$E'_5 = E_p + E_{mr} \quad (10)$$

$$E_p = k\frac{Vol}{v}\,t \;=\; E_5 \; and \; E_{mr} = k\frac{Vol_{mr}}{v}\,t \quad (11)$$

$$E'_5 = E_5 + E_{mr} \quad (12)$$

Material recovery effect is mainly related the phenomenon of thermal expansion of solidification process of metal liquid generated in UPM [33], therefore, energy component E_{mr} is highly related to the volume change of material due to the material response to the change in surface temperature,

$$Vol_{mr} \;=\; Vol\beta(T_1 - T_0) \quad (13)$$

where β is the volumetric temperature expansion coefficient, T_1 and T_0 is the final and initial temperature of the machined surface respectively.

$$E_{mr} \;= k\frac{Vol\beta(T_1 - T_0)}{v}\,t \quad (14)$$

$$E'_5 \;=\; \frac{kt}{v}\left(Vol\; + Vol\beta(T_1 - T_0)\right) \quad (15)$$

$$E'_5 \;=\; \frac{kt}{v}\left(Vol\; + Vol\beta(T_1 - T_0)\right) = \; k\frac{t}{v}(Vol\; + Vol_{mr}) \quad (16)$$

In practical, E'_5 could be determined by using equations (15) or (16), depending on the available values of parameters in the equations in the practical situations. If we consider the recovered material volume in the UPM process, the new energy consumption model for UPM E' is expressed to:

$$E' = E_1 + E_2 + E_3 + E_4 + E'_5 \quad (17)$$

$$E' = P_0 t + P_0 t_1 + P_0 t_2 \left({}^{t}/_{T_L} \right) + y_E \left({}^{t}/_{T_L} \right) + k \frac{t}{v} (Vol + Vol_{mr}) \quad (18)$$

The energy components in the energy consumption models of two representatives of UPM technologies have been classified as Figure 4, which the material recovery factor is included. For ultra-precision diamond cutting and raster milling, the material recovery factor is dominant for both, and the recovered materials reduce the assigned material removal volume significantly, and so their energy consumptions can be universally determined by the general modified equation (17).

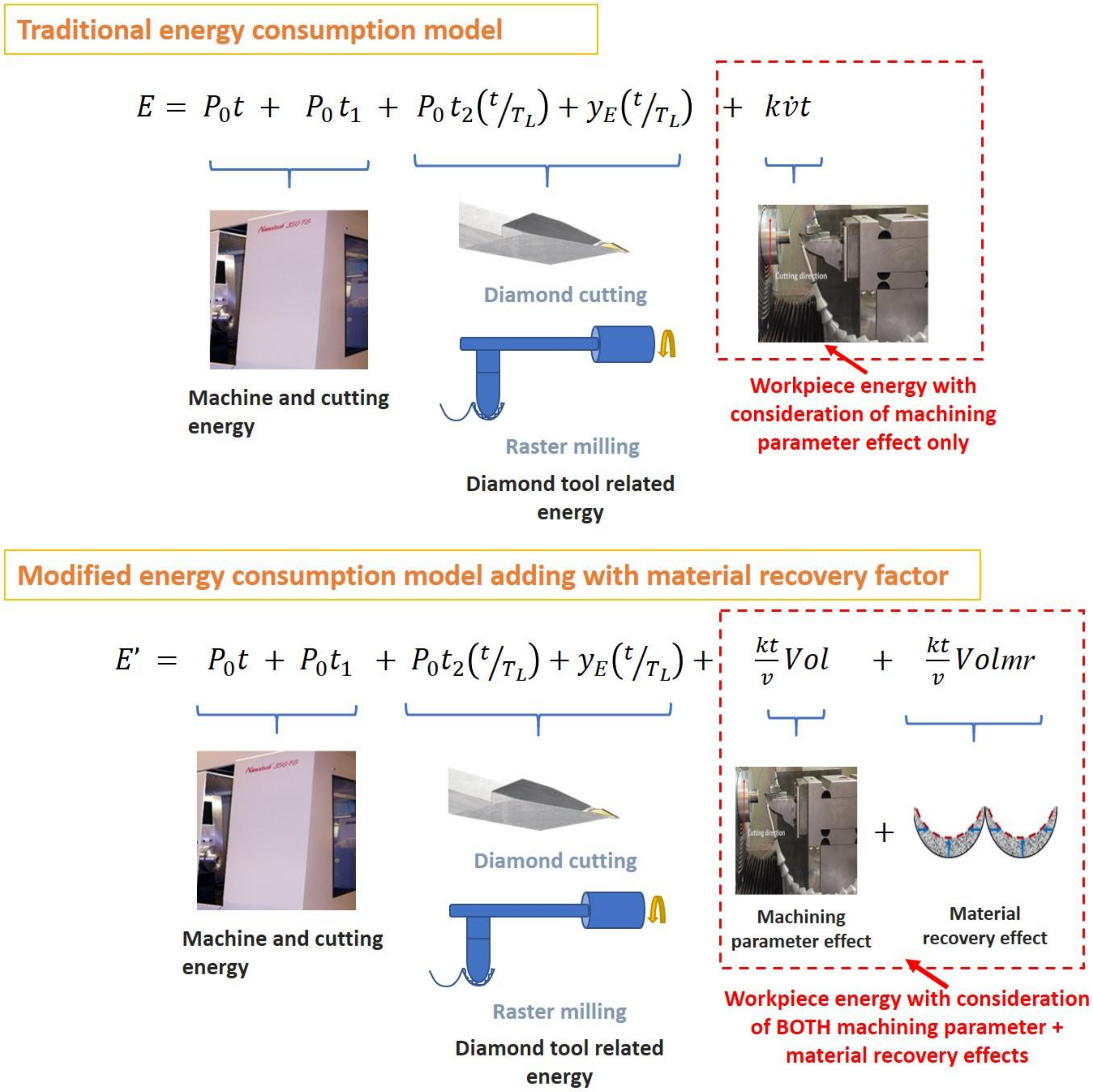


Figure 4. The traditional and modified energy consumption models

4. Experimental validation

The leading representative of UPM is currently ultra-precision diamond turning [20]. Therefore, in the experimental validation part, ultra-precision diamond cutting is used for validating the energy model proposed in this study, which it would show the comparison of the energy component for the material removal energy between the proposed E'_5 and existing models E_5. Titanium alloys would be used as the workpieces for the tests because they are the well know materials showing dominant material recovery effect in UPM.

4.1 Experimental setup

Cylindrically shaped samples of Titanium alloy, Ti6Al4V (TC4), were employed for the experiments in the case study. The Moore Nanotech 350FG (4 axis Ultra-precision machine) was used for the diamond cutting tests, which it has the components of air bearing spindle and hydrostatic motional slide. The workpiece with a diameter of 150 mm and 50mm length was mounted by a special fixture on Professional Instruments air nearing spindle of ultra-precision machine. Feedrate in the y-direction was input as cutting velocity in the diamond cutting tests. The workpiece was undergone the rough cut before starting the cutting tests as one of the standard processes in diamond cutting. The experimental setup is shown in Figure 5. The surface of the titanium alloy was underwent straight face diamond cutting with a cutting velocity of 150mm/min and depth of cut 3μm, 4μm, and 5μm, the cutting velocity was set as constant, which it ensured that cutting velocity was a fix factor regarding to the material removal rate. Therefore, 3 individual cutting profiles would be generated in the cutting tests with different depth of cut. The Wyko NT8000 Optical Profiling System was used to measure the surface profiles of the machine surface. All the cutting tests were conducted in a presence of lubricant condition.

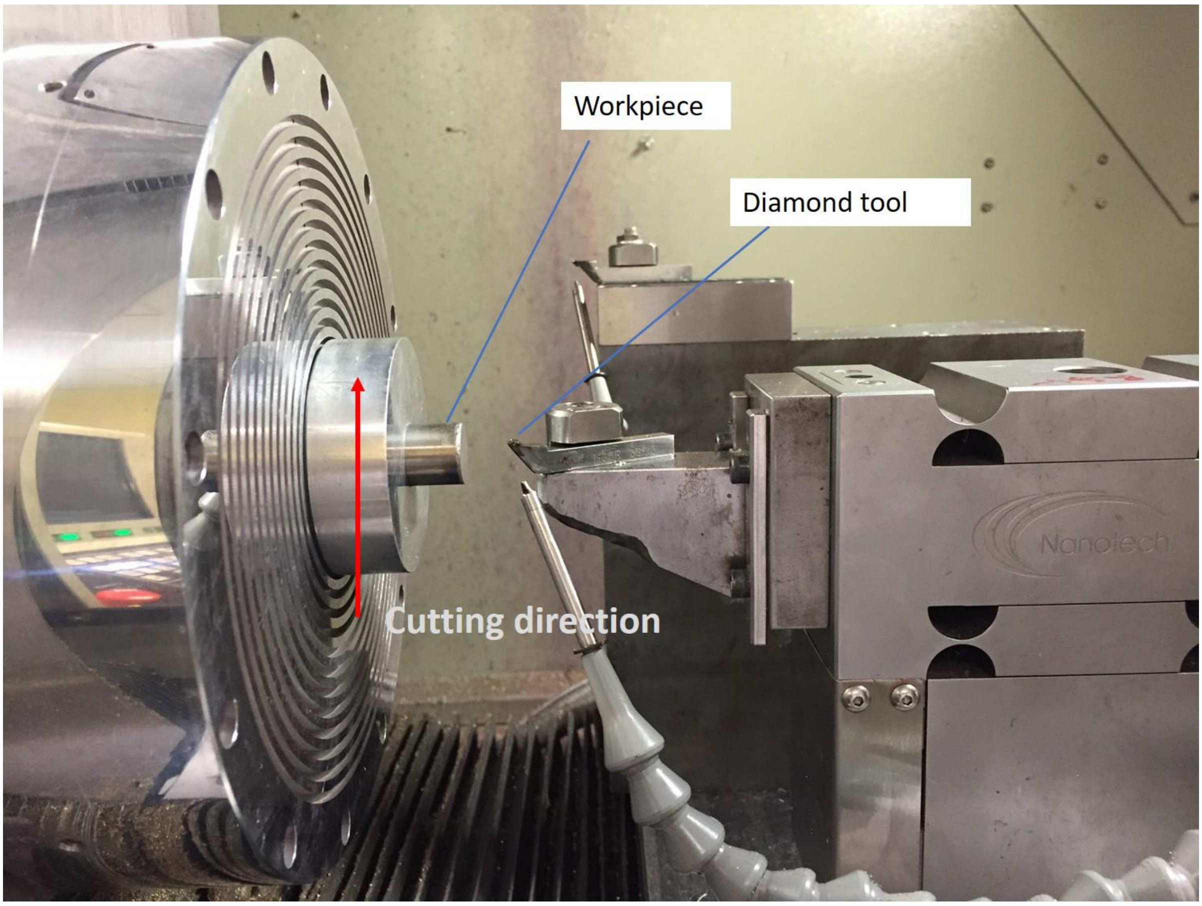
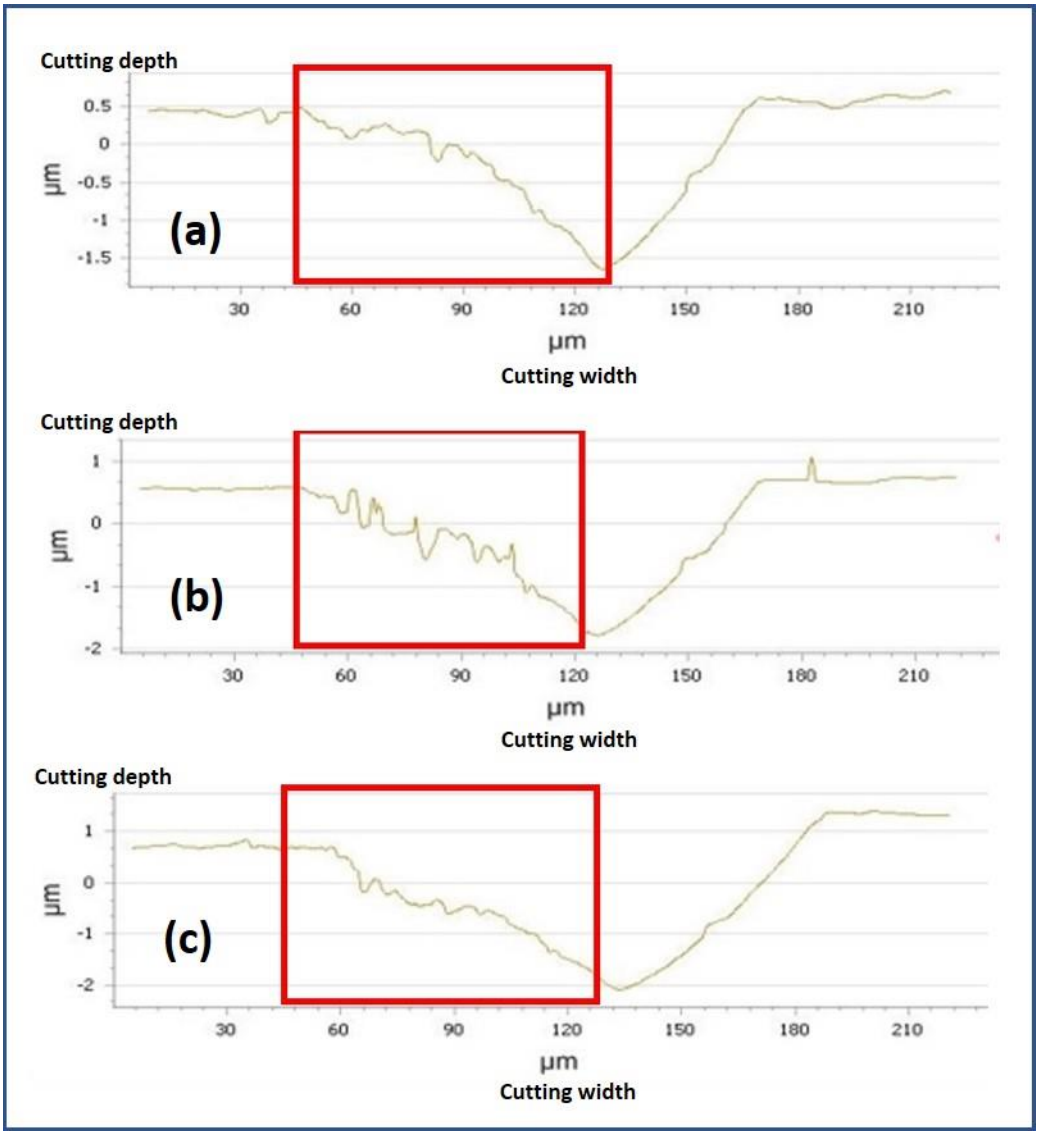


Figure 5. Experimental set of diamond cutting tests

4.2 Results and discussion

4.2.1 Cutting profiles

The cutting profiles of the machined surface under cutting depth 3μm, 4μm and 5μm are shown in Figures 6 (a), (b), (c). As shown by the red squares in the figures, a large volume of recovered materials was generated because of the material recovery effect, and it leaded to the ragged surface profiles. Actually, cutting temperature at the machined surfaces in UPM is highly localized; the deformation at shear zone occurs at relatively high strain rates which further generates a large amount of heat in cutting processes. Consequently, a large proportion of heat energy penetrates into the workpiece from primary cutting zone [33]. The generated heat flux, which is trapped inside the workpiece, leads to the occurrence of thermal expansion on the machined surface, causing the recovered and expanded surface with poor dimensional accuracy and surface quality of the workpiece. Especially for the workpiece with low thermal conductivity like titanium alloys, the higher amount of heat energy is remained into the workpiece after UPM and therefore the serious material recovery effect is resulted [15]. According to Figures 5, the recovered materials occupied a significant large area of assigned removal materials. The ratio of recovered material volume to the assigned material removal volume increased with depth of cut increase; which the material removal percentages of cutting depth and width are shown in Tables 1 and 2. The difference between assigned depth of cut and actual cutting depth, and, assigned cutting width and actual cutting width increased with depth of cut increase. For the cutting profile generated at depth of cut 5μm, the recovered width and depth of cutting profile even reached to half of assigned cutting width and cutting depth. The largest error percentages of cutting width and depth were up to 47.94% and 58% respectively. With the material recovery induced by the intensified thermal expansion in UPM, the error percentages of cutting depth and width were significantly large. This validated the theory regarding consideration of the energy component related to material removal volume in the energy consumption model for UPM, especially when cutting at the high material removal rate (relatively large depth of cut) and with high material recovery rate materials such as titanium alloys.



Figures 6. The cutting profiles of machined surface under cutting at depth of cut (a) 3µm, (b) 4µm and (c) 5µm

Table 1. Recovered material percentage of cutting depth

Depth of cut /Assigned depth of cut (µm)	Actual cutting depth (µm)	Recovered percentage of cutting depth (%)
3	1.75	41.67
4	1.78	55.50
5	2.1	58.00

Table 2. Recovered material percentage of cutting width

Depth of cut (µm)	Assigned cutting width (µm)	Actual cutting width (µm)	Recovered percentage on cutting width (%)
3	191	113	40.69
4	220	117	46.81

5	246	128	47.94

4.2.2 Material removal volume and material removal rate

With information of the diamond tool used in the experiments, and the dimension of the workpiece, the assigned material removal volume Vol_{assign} is calculated by:

$$\mathrm{Vol}_{assign} = \left(r^2 cos^{-1}\left(\frac{r-DOC}{r}\right) - (r-DOC)\sqrt{2 \times r \times DOC - DOC^2}\right) \times L \quad (19)$$

Where *r* is tool radius, *DOC* is depth of cut and *L* is the cutting length. On the other hand, the recovered material volume induced by material recovery effect in diamond cutting Vol_{mr} is:

$$\mathrm{Vol}_{mr} = \mathrm{Vol}_{assign} - Vol_{actual} \quad (20)$$

$$= \left[\left(r^2 cos^{-1}\left(\frac{r-DOC}{r}\right) - (r-DOC)\sqrt{2 \times r \times DOC - DOC^2}\right)\right] - Vol_{actual} \quad (21)$$

where Vol_{actual} is the actual material removal volume in the diamond cutting procedures. The calculated results of $Vol_{asssign}$, Vol_{mr}, Vol_{actual} and the percentage of Vol_{actual} are shown in Table 3. Referring to Table 3, the recovered material volumes induced by the material recovery effect were all over 74% of the assigned material removal volume, which the percentage of actual removal material volume to the assigned removal material volume was below one quarter for the machining conditions at depth of cut 3µm to 5µm. Especially at depth of cut 5µm, the percentage of recovered material volume reached to 83.61%. The exceptionally large proportion of recovered material volume leads to inaccurate application of traditional and previous energy consumption models in UPM, especially for the workpieces with low elastic modulus like titanium alloys.

Table 3. Assigned material removal volume, recovered material volume induced by material recovery, and the percentage of actual material removal volume

DOC(μm)	Vol_{assign}(μm^3)	Vol_{mr}(μm^3)	Vol_{actual}(μm^3)	Vol_{mr} percentage (%)
3	5716901	4233776	1483125	74.06
4	8800873	7238923	1561950	82.25
5	12298374	10282374	2016000	83.61

4.2.3 Analysis of the energy model for ultra-precision machining

The case study proves that the material removal volume in traditional/previous energy models of UPM significantly changes because of the dominant material recovery effect. In this section, the energy component related to the material removal volume E_5 is investigated mainly. The traditional energy component related to material removal volume E_5 and the modified one $E^{'}_5$ are both shown in Table 4. According to Vincent and Mativenga [12], the specific cutting energy for titanium alloys is 1.13 Ws mm^{-3}, therefore E_{mr}, E_5 and $E^{'}_5$ can be obtained.

Table 4. Values of E_{mr}, E_5 and $E^{'}_5$ generated at different depth of cut

Depth of Cut (μm)	E_{mr} (J)	E_5 (J)	E'_5(J)	E'_5/E_5	Increased accuracy percentage of proposed energy component E'5 (%)
3	0.0003189	0.0004307	0.0007496	1.17	74.04
4	0.0005453	0.0006630	0.0012083	1.55	82.25
5	0.0007746	0.0009265	0.0016991	1.83	83.39

As shown in Table 4, with the consideration of recovered materials in diamond cutting, the energy consumption related to material removal volume $E^{'}_5$ was comparably high, which the ratio of $E^{'}_5$ to E_5 reached to 1.17-1.83; E_5 was only nearly half of the value of energy consumption obtained in the practical case. In machining processes, previous researches constructed the hypothesis that the machined materials at the cutting zone with shear deformations would suffer from microscopic plasticity when the uncut chip thickness is below a critical value [34]. Because of the undeformed chip thickness of titanium alloys appears differently from other metals in UPM, therefore, for the case with the consideration of material recovery effect, energy consumption is higher because of the additional deformation energy for the material swelling effect in UPM of titanium alloys. The results from the case study showed that the energy usage of material removal volume obtained in traditional energy consumption models markedly differs from the practical case and the proposed one. On the contrary, due to the inclusion of the material recovery factor to the energy component E'_5, the accuracy percentage for E'_5 increased up to 83.39%. The energy component of E_5 should be modified as E'_5 in the energy consumption model of UPM.

4.2.4 Specific energy consumption of ultra-precision machining

Specific Energy Consumption (SEC) is defined as the ratio of total energy consumption to the effective output of the operational process, which it is commonly used as one of energy efficiency indexes nowadays [35,36]. SEC becomes one of the critical indicators for the assessment of energy efficiency in machining. Wang et al. [35] showed that the energy flows of different layers within a machining system in manufacturing were distinctive from each other, and therefore the energy efficiency index of each layer should be determined individually. The material removal process in manufacturing belongs to the machine tool layer, which focuses on the energy breakdown of the machine tool. Wang et al. [35] suggested that SEC of the material removal process at the machine tool layer should be determined individually because of the nature of the distinctive layer, and it is denoted as SEC_M:

$$SEC_M = \frac{Material\ removal\ energy}{Material\ removal\ volume} \quad (22)$$

therefore, specific energy consumption of traditional models SEC_M for ultra-precision machining is:

$$SEC_M = \frac{E_p}{Vol_{assign}} \quad (23)$$

if the material recovery effect in UPM is considered for SEC, the new specific energy consumption of the proposed model SEC'_M is:

$$SEC'_M = \frac{E'_5}{Vol_{assign} - Vol_{mr}} \quad (24)$$

The results of SEC_M and SEC'_M obtained in the diamond cutting tests at depth of cut 3µm - 5µm were determined and are shown in Table 5 and Figure 7. The values of SEC_M for the traditional model were all the same at depth of cut 3µm - 5µm; as anticipated, this means that the energy consumed per one cubic millimeter volume was the same under the machining conditions of different depth of cut for the same material. However, SEC_M is not able to reflect the value of it in the practical situation of diamond cutting in UPM, because the level of material recovery effect increases with depth of cut increase, as shown in Table 6. Actually, as the uncut chip thickness decreases, the ploughing motion of cutting tool and the material recovery effect occur, consequently they lead to an increase in the specific cutting energy nonlinearly, [37]. On the other hand, an increase in the specific energy consumption in cutting is caused by an increase in material strength of machined surface, which are mainly induced by the large temperature gradient and strain rate effects [38]. Therefore, actual energy consumed for removing of one cubic millimeter volume should be increased when depth of cut increases, and, SEC'_M increased with depth of cut increase too. The values of SEC'_M obtained by the proposed energy model were proven to practically match with the machining characteristics in UPM. Furthermore, by applying a higher depth of cut in the cutting tests, an increased percentage of SEC'_M was obtained; the value of SEC'_M was even larger than SEC_M by about 11.2 times at depth of cut 5μm. With the consideration of the material recovery effect for the energy model of UPM, the values of SEC'_M were unexpectedly higher than that of traditional models. Due to the neglection of the material recovery effect in the calculation of energy components in the traditional energy models, the fundamental error of SEC_M is committed; the error percentage of SEC_M increases with depth of cut increase, which the error percentage of SEC_M determined by traditional model reached from 571% - 1020%, the underdetermination of SEC_M in the traditional approach was revealed in this case study.

Table 5. SEC_M and SEC'_M at depth of cut 3μm - 5μm

Depth of Cut (μm)	SEC_M (J/mm^3)	SEC'_M (J/mm^3)	Increased time for SEC'_M	Error percentage of SEC'_M (%)
3	0.07533	0.50543	6.7	570.93
4	0.07533	0.77360	10.27	926.91
5	0.07533	0.84379	11.2	1020.08

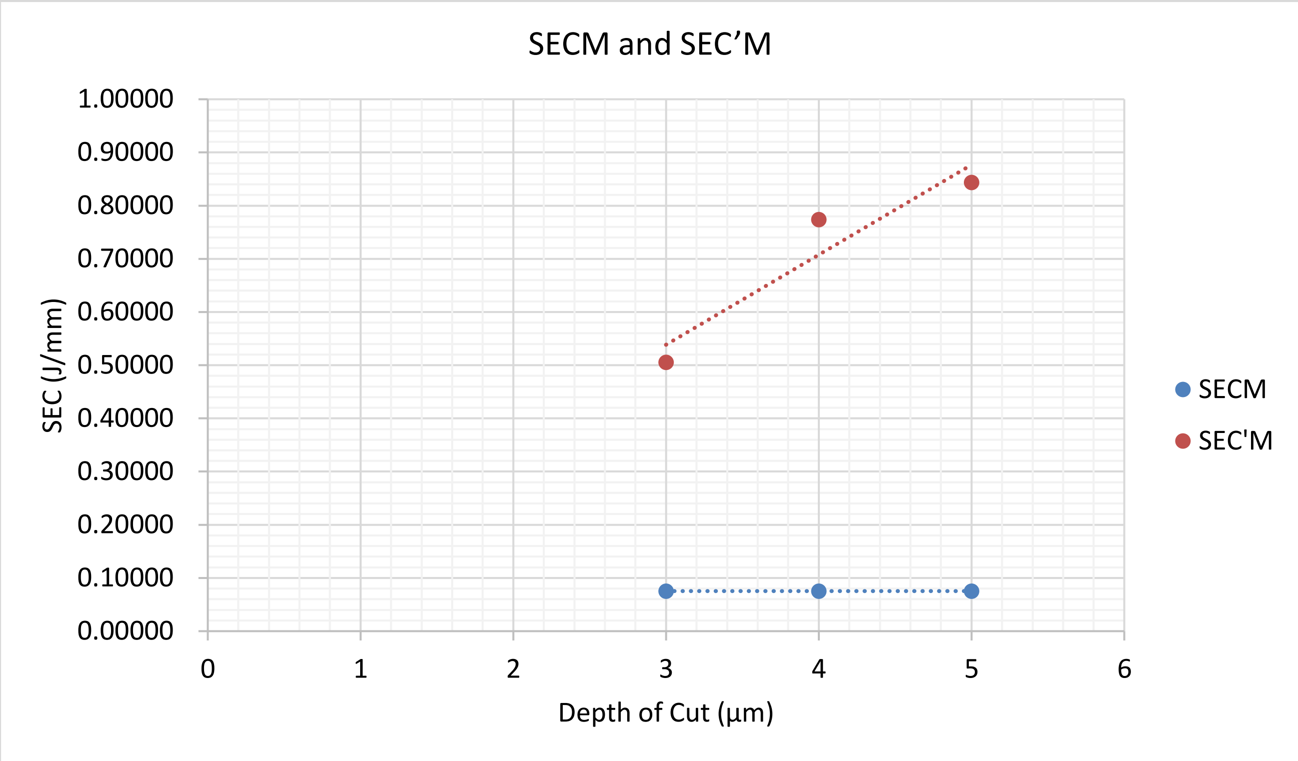


Figure 7. SEC_M and SEC'_M at depth of cut 3µm - 5µm

4.2.5 Machining strategies for reducing the energy consumption in UPM

The additional energy was consumed to take the material recovery effect effective in UPM referring to the previous sections. A reduction of material removal energy for generating recovered materials E'_{mr} could decrease the overall energy consumption in UPM significantly. There are few literatures reporting the reduction of material recovery effect by different techniques such as tool path optimization, cryogenic assistance [39], ultrasonic vibration [40] and magnetic field assistance techniques [13]. By reducing the recovered materials, the energy component E'_{mr} could be decreased to near the value obtained in the traditional approach. However, as the extra energy is needed to provide for operating machines or facilities for ultrasonic vibration assistance in order to suppress the recovered materials, therefore, machining technologies such as magnetic field assistance and optimal tool path, which they consume relatively low energy, are highly recommended.

5. Conclusion

An accurate determination of energy consumption in manufacturing processes provides supports for the establishments of energy saving strategies for industries. However, since the energy component of the material removal process does not involve the material recovery effect into the traditional energy consumption models, therefore, these models demonstrate a large error for the real energy consumption value in the UPM processes. This study therefore proposes a modified energy consumption model with the consideration of material recovery effect, which is the dominant material factor involved in UPM. The case study of diamond cutting tests, which is the representative machining technology in UPM, showed the error percentage of the traditional energy consumption model was exceptionally large. This study demonstrates the importance of the material recovery effect on the energy consumption model of UPM. Below are the notable contributions and findings from this study:

1. The percentage of recovered material volume in UPM of titanium alloys reached up to 83.61%. The exceptionally large proportion of recovered material volume leads to large error of determination of traditional energy consumption models for UPM, especially when the significant material recovery effect happens in UPM.
2. The unique material recovery effect factor should be included in the energy consumption model of UPM in order to show the dominant material recovery effect in UPM processes. The model can be applied to UPM by considering the approximate material removal volume of actual and assigned cases, the flexibility of the uses of this model increases.

3. As the influences of the material recovery factor on the energy component E'_5, the accuracy percentage for E'_5 increased up to 83.39% and the actual specific energy consumption SEC'_M proposed by this study was up to 11.2 times in comparison to the result obtained in the traditional energy consumption model.
4. This study reveals that the energy consumption energy could be reduced significantly by reducing the level of material recovery, it becomes the new direction to researchers and industries to construct the energy saving plan for the fabrication activities of UPM.

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