https://doi.org/10.1016/j.jmapro.2020.08.020

Preliminary investigation on ultra-precision diamond turning of titanium alloys using thermoelectric cooler fixture

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Abstract

The low thermal conductivity of titanium alloys causes an accumulation of high cutting heat at the tool/workpiece interface and thus deteriorates surface integrity of the machined surface in ultra-precision machining (UPM). In response of this underlying source causing the poor machinability of the materials in UPM, in this study, a novel fixture composed of thermoelectric cooler (TEC) is firstly developed and applied into single point diamond turning (SPDT) of titanium alloys, aiming to dissipate the cutting heat in the machining process. The TEC contacted with workpiece during the whole turning process and caused a dissipation of cutting heat from the workpiece. By using the fixture with TEC device, the cutting force variation and surface roughness involved in SPDT were reduced. This study presents the preliminary results of application of TEC fixture on UPM of titanium alloys and shows the feasibility of the use of TEC device in UPM area, suggesting a new approach to resolve the problematic high cutting heat of titanium alloys in UPM.

Keywords: Thermoelectric cooler, Titanium alloys, Machinability; Single point diamond turning; Cutting heat

1. Introduction

Although titanium alloys have the excellent material properties such as high strength to weight ratio and high chemical resistance, they are difficult to cut materials and their machinability is poor in comparison to other common alloys. Titanium alloys have low thermal conductivity, the high cutting heat is localized at the tool/workpiece interface in machining processes, this results in excessive material swelling, tool wear, and cutting force, all of which worsens surface integrity of the machined surface especially in ultra-precision machining (UPM). Actually, the cutting mechanism of titanium alloys is extremely complicated and different from traditional alloys [1] . Especially for the problematic material swelling effect, the machined surface of titanium alloys in UPM demonstrated serious material recovery, which a large amount of cutting heat is accumulated at the tool/workpiece interface and intensifies the volume from material recovery. Material swelling effect is a type of natural response of materials properties which is unavoidable [2]. For tool wear, adhesive tool wear is typically resulted in diamond turning of titanium alloys as high cutting temperature is involved. In UPM, small fragments of titanium alloys are attached to the diamond tool tip and the lateral tool edge during machining, which diamond tool wear is further intensified under continuous diamond machining [3]. Because of high tool wear rate and material swelling effect, surface roughness of UPM of titanium alloys has rarely reached to lower than 10nm [4], which this is the UPM requirement for its fabricated surface. The drawbacks from high cutting temperature in UPM of titanium alloys lead low machinability of the materials, therefore, an evolutionary machining technique is required to reduce the problematic high cutting heat and thereby enhances the machinability of titanium alloys in UPM.

A thermoelectric cooler (TEC) is a promising device for providing rapid cooling to an attached component. A TEC is also known as a Peltier Cooler because it applies the Peltier effect for removing surrounding heat from the environment [5,6]. The working principle of TEC is based on the movement of an electric current across two junctions of different conductors, which are called thermocouples. The heating effect between these two conductors does not mainly follow Joule heating effect lonely, in fact, based on the direction of current flowing, the heating condition could be either heating or cooling. For the cooling effect induced by the Peltier effect, the heat of an attached object could be dissipated effectively by using TEC. A TEC comprises several n-type and p-type semiconductors as the thermoelements, which are linked electrically in the series position using copper strips. They are positioned as sandwich structures and located at the middle layer between two electrical insulated ceramic plates. Although the ceramic plates are electrically isolated, they are thermally conductive so that the cooling effect can be provided. During the operation of TEC device, the electrical current flows from the n type thermoelements to the p type thermoelements [7]. The temperature T_c at the side of cold junction decreases and the heat is conveyed from the surrounding environment to the cold junction at the lower temperature. In the operation process of TEC, electrons go from the low energy state within the p type thermoelements to the high energy state within the n type thermoelements of the cold junction. Simultaneously, the moving electrons take the absorbed heat energy from hot junction side where the temperature there is T_h. As a result, the heat is dissipated effectively through the heat sink attached to the TEC device. Finally, the electrons return back to the lower energy state within the p type semiconductors. In the case of an existing temperature difference between the cold junction and the hot junction of n type and p type thermoelements, the voltage generated inside the TEC device would be directly proportional to the temperature gradient between the cold and hot junctions.

The TEC has been widely applied in many industries, especially electronics [8]. The expected junction temperature from a common chip package in electronic components is normally higher than hundred degrees Celsius, whereas the suitable operating temperature for a junction inside the component should be less than 85 Celsius [9]. The application of TEC provides a fast solution to this challenging problem by using a passive cooling technique. Other than the electronic industry, the TEC device is also suggested for other applications such as refrigerators, cooling systems for car seats, semiconductor lasers and sensors [10]. The cooling effect of a TEC device is proven through its widespread application.

The excellent cooling performance from a TEC device could be utilized for responding to the machining problem of high cutting heat generated in UPM of titanium alloys. The temperature of an object attached to a TEC device could drop to below zero degrees within a half-minute, which would reduce the immediate cutting heat. Therefore, the cooling effect induced by the TEC device minimizes the high cutting heat generated in UPM of titanium alloys, providing the fast cooling influence on the tool/workpiece interface. In this research, a specifically designed fixture installed with a TEC device is used for holding a workpiece in an ultra-precision machine, with the aim of providing an online cooling effect to the workpiece during single point diamond turning (SPDT); the fixture with TEC device efficiently dissipates the cutting heat at the tool/workpiece interface. Experimental results relating to the cutting force, cutting force variation, chip formation, and surface roughness, under the influence of the TEC device are shown and compared with tests using a fixture without a TEC device. The TEC device applied to UPM delivered machining outcomes that greatly improved the machinability of titanium alloys.

1.1.Designed fixture with TEC device

Thermoelectric cooling is a cooling technology using a TEC device. In order to deliver the advantages of high reliability and superior cooling with a compatible size TEC device, the operation environment of TEC should be stable and the surrounding environment in the operation must enable sufficient dissipation of the heat from the hot junction [11]. Therefore, the structure of the fixture for this study was designed to ensure stability of the working environment for the TEC device during SPDT of the titanium alloy sample. Another advantage of TEC is that it can be powered and operated by a direct current (DC) source whose comparatively small size allows for a low weight non-bulky design suitable for mounting on the fixture of the ultra-precision machine. In addition, an elimination of the need for electric wires to be connected to the TEC device makes the rotational motion of the fixture during SPDT feasible. The design of the fixture with the TEC device for SPDT of titanium alloys used in the experiments is shown in Figure 1. The TEC fixture is composed of few parts, all of which allow for effective heat dissipation through the TEC device during the cutting tests and the stable contact of the workpiece to the TEC device. The TEC device is placed on top of the heat sink, and the workpiece is installed on the top of the TEC device and locked in place by screws. There are eight slots positioned on the side of the TEC that provide space for the cooling air to flow inside the heat sink through the rotational diamond turning motion. As the aerodynamic effect of the rotational motion of the fixture in SPDT induces cool air to flow into the TEC device from the surrounding environment, the fixture does not need to have an extra cooling component such as an electronic fan, thereby saving energy and promoting green manufacturing. However, proper design of a heat dissipation system for the TEC device is important so that it removes the restrictions of high system cost, low energy efficiency, and low operation reliability. The TEC device is turned on during the SPDT process, which provides a cooling effect and resolves the problem of excessively high heat during the SPDT of titanium alloys.

The issue about thermal shrinkage has been considered into the experimental setup. Actually, the thermal shrinkage problem will affect the tool calibration and the setting of the relative tool position to the workpiece significantly; once the workpiece has thermal shrinkage, the relative position of tool/workpiece will shift from the original setting one, and therefore highly affect the precision level of machined surface. In order to deal with this problem, the TEC device was turned on for a while with the confirmation of unchanged of surface temperature before conducting SPDT in the experiments, and therefore the size of the workpiece did not change anymore with time in SPDT. Also, the stabilization of surface temperature before conducting SPDT ensured the minimization of temporary thermal softening effect and the change in cutting force induced from it. After that, the workpiece underwent the final tool calibration and was conducted SPDT processes. The relative of tool position and the workpiece and the pre-set tool path and other cutting parameters were more accurate.

On the other hand, the measurement of cutting temperature in ultra-precision machining is always problematic and unavailable because of limited technological measurement tools currently. In UPM, the cutting zone at the tool tip is extremely small which the size of the cutting area is normally range at micro-range, the cutting temperature therefore is hard to measure by physical measurement tools such as thermal cameral or infrared camera. However, the submitted works are preliminary results and the first investigations for TEC devices in UPM of difficult to cut materials, which it is the starting stage of the research of this direction. The simulation and model will be built up in getting sufficient data experimentally with validation tests by applying the modified TEC fixture in future.

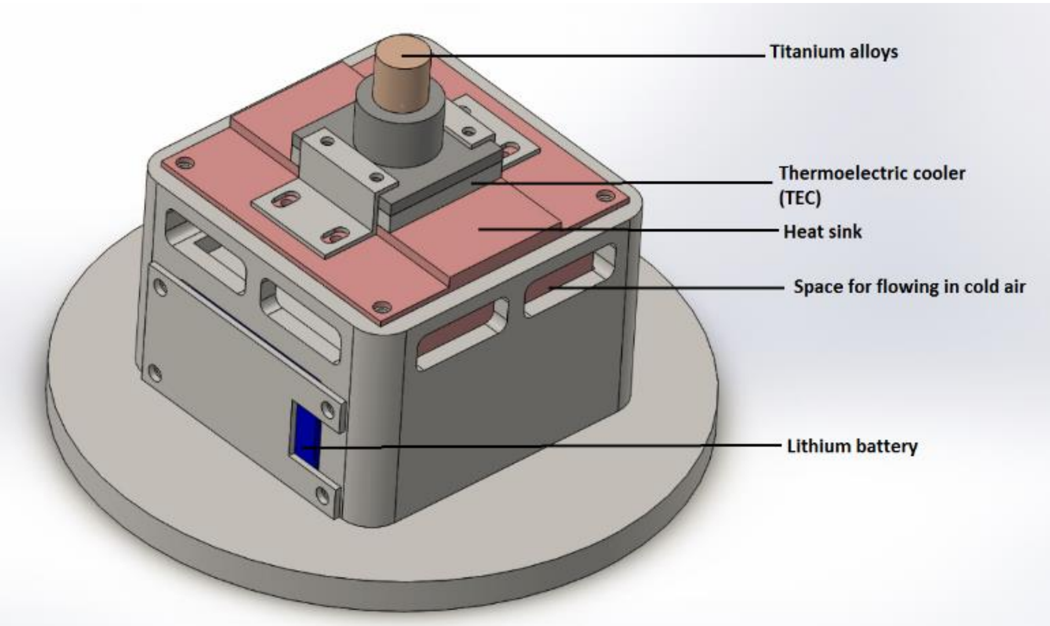


Figure 1. The TEC fixture used in SPDT of titanium alloys

2. Experimental setup

Ti6Al4V (TC4) were used as the workpiece material for the experiments. The two workpieces were cylindrically shaped with a length of 25mm and a diameter of 16mm. One workpiece underwent SPDT using the TEC device and was named the TECS (Thermoelectric cooler sample), while the other workpiece underwent normal SPDT without using the TEC device and was named the NTECS (Non-thermoelectric cooler sample). As the environmental concern, the TEC fixture did not include the cooling fan in order to save the electricity energy. The rotational motion of the TEC fixture during the SPDT process would provide the cooling function to the hot side of TEC device in the fixture. The radius and height of the diamond tool were 0.985mm and 3.694mm respectively. The chip formation generated from the turning experiment was observed using Hitachi HT3030 scanning electron microscopy (SEM) machine. Kistler 9256C force sensor was used to measure the cutting forces in two directions. The setting of sensitivity for Kistler is 24.63. The natural frequency of Kistler is 5.1KHz. The sample rate of capturing data point is 50k, which the rate is determined for sufficiently capturing the cutting forces in entire machining cycle with expectations of cutting force range and scale. Kistler has a matching software called “Dynoware”. Dynoware is used for analysing cutting force data and showing cutting force data with synchronizations. The force sensor applying in the experiments uses the approach of piezoelectric measuring chain, therefore, the sensor may have electrical drift, it means the zero point of the output signal will move to negative or positive value of y-axis. Dynoware has the function of “drift compensation”, which this function was turned on every time when observing the force data in Dynoware. With the built-in function of drift compensation for Dynoware, the drift error was enabled to reduce. Moore Nanotech 350FG 4 axis Ultra-precision machine was used as the equipment for diamond turning. Wyko NT8000 Optical Profiling System was used to measure the values of surface roughness, overall five different areas over the machined surface with 2.5 mm linear interval distance aligning with the workpiece centre were measured, surface roughness of the particular areas was averaged to avoid from the bias of extremely large or small values. The values of surface roughness in this study are demonstrated as Sa, which it is average roughness evaluated over the complete 3D surface, and it denotes as an absolute value and the results of the difference in height of each point measured over the surface and the arithmetical mean of the surface. Feedrate, depth of cut, and spindle speed were set as 8mm/min, 3μm, and 1500rpm respectively and remained unchanged throughout the experiments. The machining parameters chosen in the experimental setup such as cutting depth, feedrate and spindle speed were the optimum machining parameters which the author obtained in previous experiments, aiming to remove the other disturbances in machining such as serios tool wear and chip tangle from unsuitable machining parameters. The experiments with same machining parameters were conducted for three times to ensure the repeatability and demonstrate the correct trend of cutting forces generated in entire turning processes. The experimental set up is shown in Figure 2.

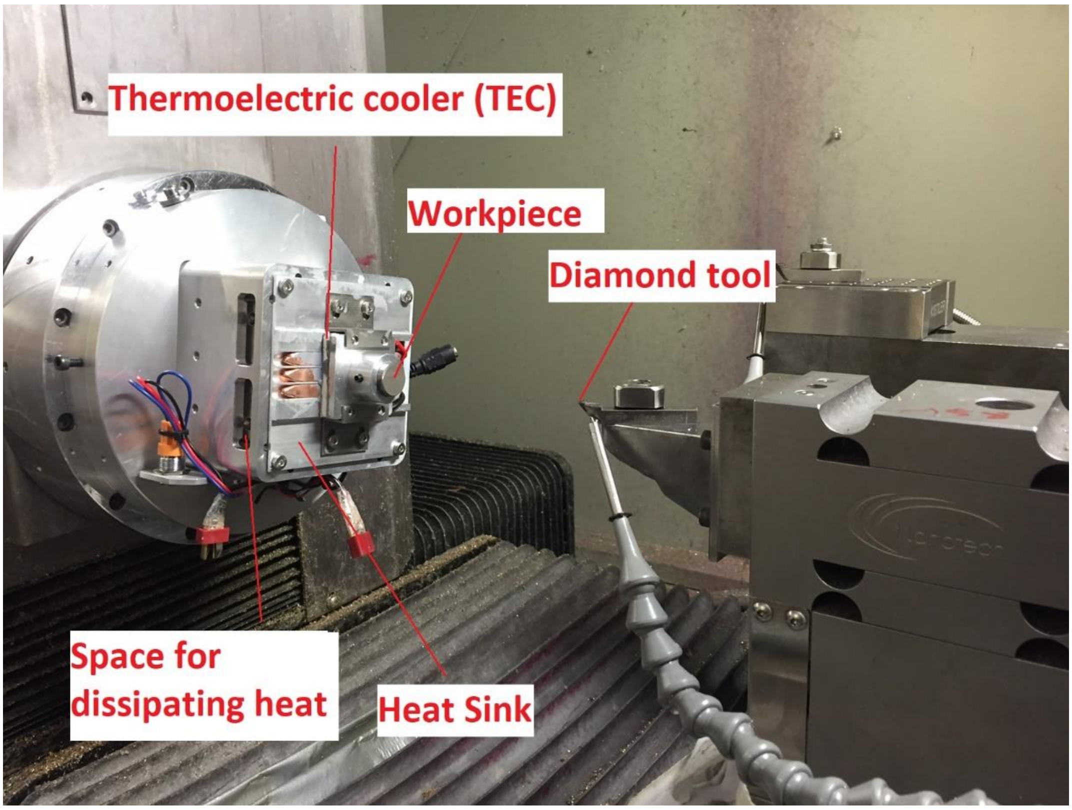
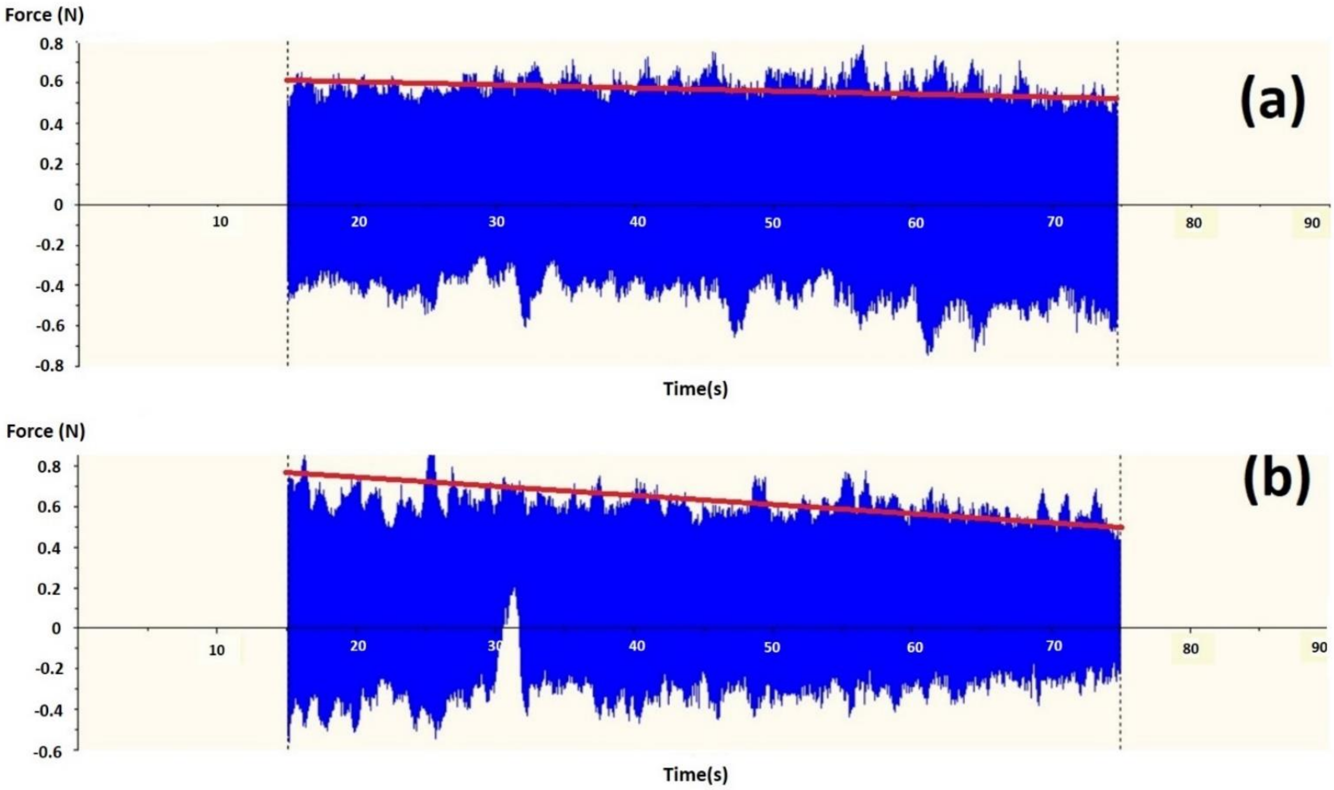


Figure 2. The experimental setup of diamond turning using TEC device

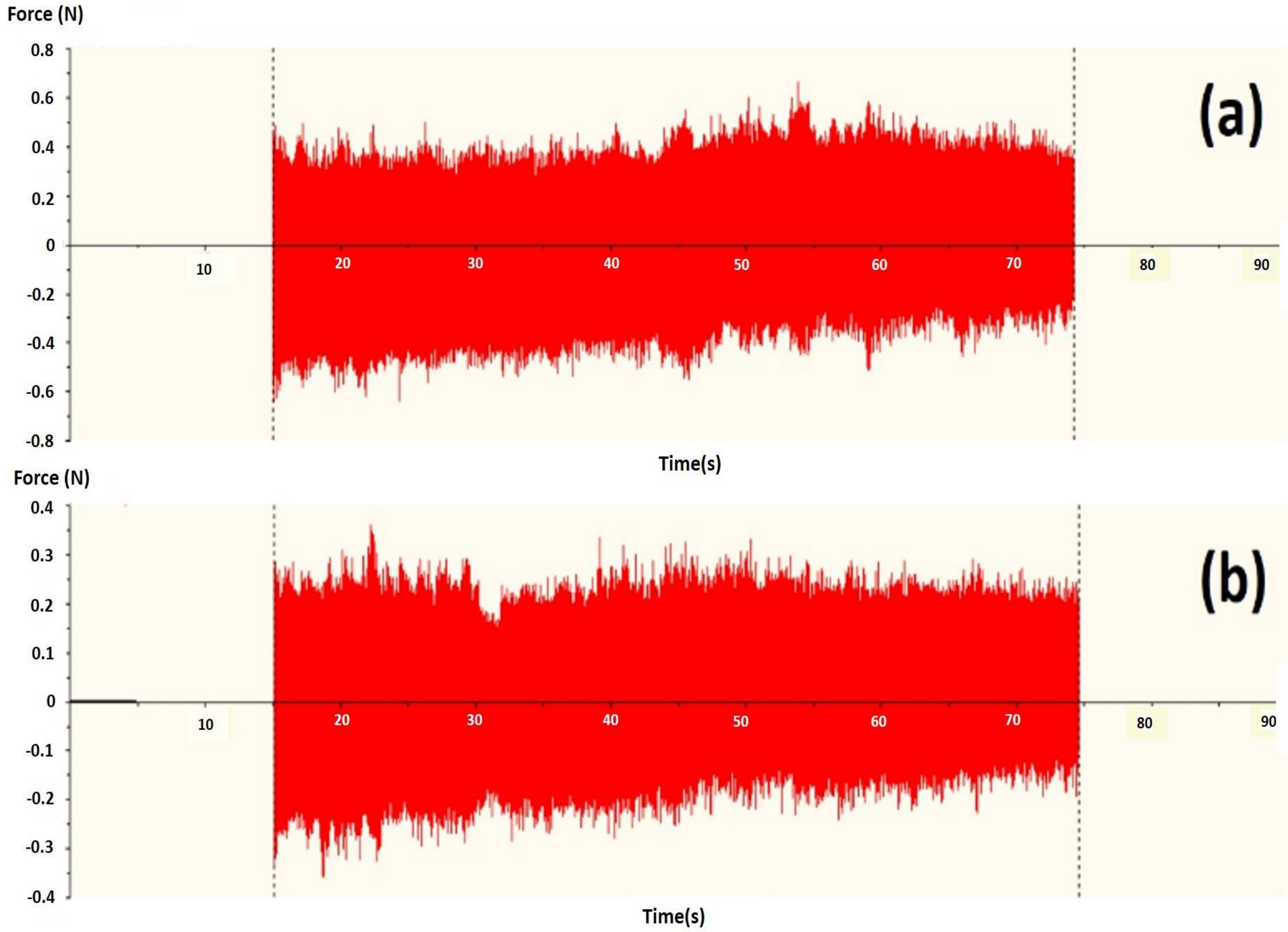
3. Results and discussion

3.1 Cutting force analysis

The cutting forces generated in the turning process of the TECS and the NTECS are shown in Figures 3 and 4. Because of the cooling effect of the TEC device, the cutting heat generated during diamond turning was dissipated efficiently. The cutting forces of the sample under the influences of the TEC device are expected to be lower. As shown by the aforementioned figures, the thrust force (F_t) of the TECS are significantly lower than that of the NTECS. The reduction percentages of maximum F_t of the TECS are 28%. The maximum value of the cutting force at certain point in the entire machining process was automatically determined by Dynoware, which Dynoware has the in-built function for determining maximum. Other than the observation of cutting force amplitude, the cutting force variations and trends are also examined in order to study the machining performances of diamond turning under the TEC device. An increase in cutting force variation is normally caused by an uninterrupted tool edge deterioration and load-interfered tool deflection in the continuous cutting process [12]. The cutting force variation of F_t of the TECS is obviously smaller than that of the NTECS, where the decreasing slope of F_t (F_t/T) is much flatter than for the TECS, as shown by the red straight line in Figures 3; the thrust force of the NTECS was undulating throughout the cutting process. Therefore, the thrust force variation of the TECS decreased in the presence of the TEC device, explaining the lessening of cutting interruption and tool deflection under the influences of the TEC device. On the other hand, according to a previous study, swelling of material in UPM is normally accessed through F_t [2]; the higher F_t magnitude, the higher level of material swelling on the machined surface. The larger value of F_t for the NTECS implied a higher material swelling effect is placed on the machined surface of the NTECS, which was induced by the extremely high cutting heat localized at the cutting zone. The effect of effective thermal conductivity on the coefficient of thermal expansion of materials has been academically established [13]: the essential differential expansion of materials under the influence of thermal gradient causes the transition of momentum between particles and gives out the condition of particle vibration, resulting in increased material volume as the separation distance between each particle is treated as thermal expansion. Because of the low thermal conductivity of titanium alloys, the cutting heat is trapped at the tool/workpiece interface, the high residual heat energy promotes the thermal expansion of materials after the sonification of melted metals, intensifying the material swelling effect of titanium alloys in UPM. Therefore, without the cooling effect delivered by the TEC device, the level of material swelling would be higher for the NTECS, and surface integrity of the NTECS would be poorer. By contrast, a smaller F_t for the TECS means a lower level of material swelling on the sample, providing evidence for the effectiveness of cooling by the TEC device. However, for the tangential force shown in Figure 4, the tangential force of TEC is slightly higher than that of NTEC, the potential reason may be due to the mechanical vibration of TEC device during the operation of TEC device in single point diamond turning, this may compensate the benefit of cooling effect from TEC device to UPM process. As this paper is the first article to report for the application of TEC device to UPM, this part would be focused and left for the research relating to the fixture with TEC device in future.



Figures 3. The thrust forces of (a) TECS and, (b) NTECS



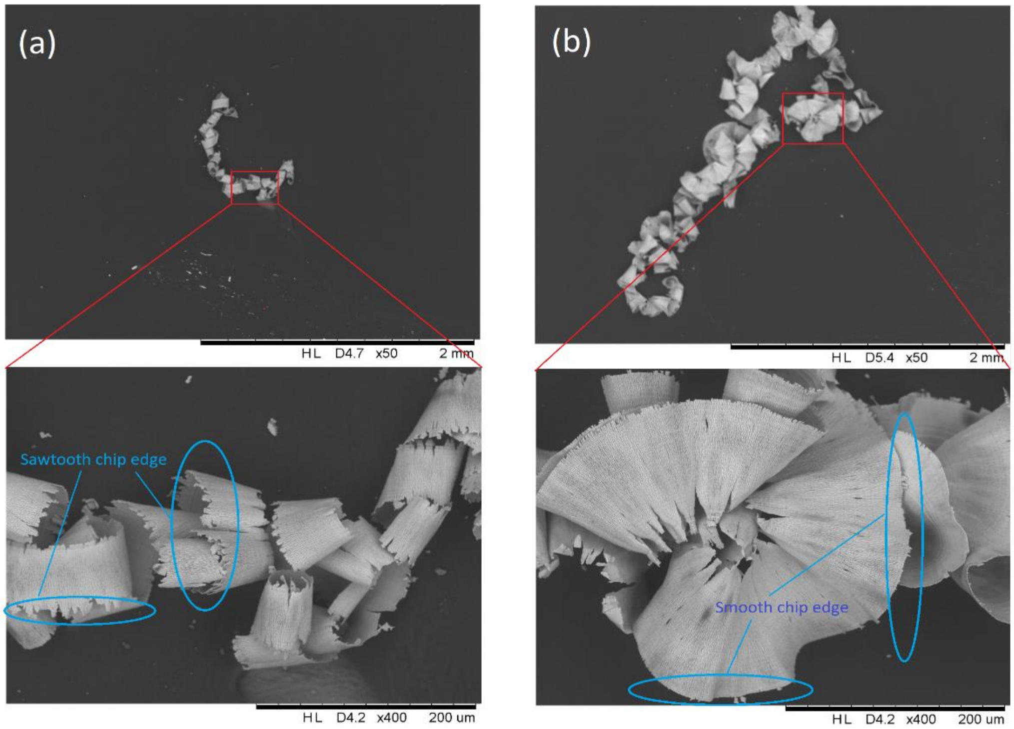
Figures 4. The tangential forces of (a) TECS and, (b) NTECS

3.2 Chip Formation

Generally, the chip formation and the types of chip are resulted from the integral effects of work material properties and cutting conditions [14]. The chip formations of the NTECS and the TECS were observed under SEM. Although the chips generated from both samples are continuous chips, the size and the length of the entire chips of the two samples are totally different. According to Figures 5 (a) and 5 (b), the length of the chip for the TECS was obviously much longer than that of the NTECS, extremely long continuous chip was generated in the turning process of the TECS under the cooling effect of TEC device. In response to the relationship between the chip formation, cutting forces and cutting temperature, the micro-fluctuation of the cutting forces in generating NTECS likely caused the shift of shear plane in the chip formation and therefore the breakage of the continuous chip, explaining the shorter chip formation of NTECS.

The effectiveness of the cooling effect of the TEC device on ultra-precision turning is further shown by the curvature of the chips generated from both samples used in the experiment. One of the reasons for the variation in the chips' shape and size can be explained by the thermal softening effect at the freshly cut machined surface and the chips generated in the cutting process. In the turning process, the cutting heat generated is localized at the primary cutting zone, such that the temperature is higher at the lower surface of the chip and lower at the upper surface of the chip. As a result, the temperature gradient is created in the upper and lower surfaces of chips, causing the formation of thermal bi-metallic spring chip shapes [15,16]. If temperature at the lower surface of a chip is higher than that of the upper surface of chip, the thermal stresses introduced by the temperature difference caused the chip to curl and tangle. If under the condition of no considerable temperature gradient, the chip would be generated in a much flatter shape. According to Figures 5(a) and 5(b), higher radius and curvature of chips were generated for the NTECS, the highly curled chip was shown in the chip formation of NTEC. The curled chip for the NTECS implies the high temperature difference between the upper and lower surfaces of the chip, which is the common machining outcome in diamond turning of low thermal conductivity alloys. On the other hand, due to the superior cooling effect from the TEC device, temperature at the primary cutting zone of TECS decreased significantly, which reduced temperature on the lower surface of chips, leading to a decrease in the temperature gradient between the upper and lower surfaces of chips. Therefore, a flatter chip was generated for the TECS. In addition, a decrease in the level of curled chips reduced the mess during the chip formation which supported the generation of long continuous chips.

The magnified shape of chip edges for both the TECS and the NTECS are shown in Figures 5(a) and (b). The sawtooth edge of NTECS chip is denoted by a blue circle, while the smooth and non-wavy chip edge is shown on the chips generated in the TECS. The formation of a sawtooth-edge chip was caused by the fluctuation of cutting forces in the machining process [17], and the thermomechanical shear instability induced by high cutting heat [18]. Therefore, the sawtooth-free edge of the chips generated by the TECS is explained by the suppression of cutting force fluctuations in the cutting process by the TEC device, which concurs with the cutting force analysis. Also, the cooling effect of the TEC device lowered the thermomechanical shear instability in the chip formation, providing a smooth chip edge and enhancing the entire chip surface. The above experimental results provide an evidence of the TEC devices' cooling effect, on the machinability of titanium alloys in ultra-precision machining.



Figures 5. The chip formations of (a) NTECS and, (b) TECS

3.3 Surface roughness

As surface roughness is extensively used to access machining quality, roughness of the machined surface after using the TEC device was measured and comprehensively analysed for this study. Average surface roughness of both the TECS and the NTECS is shown in Figure 6. Because of the cooling effect delivered by the TEC device, fewer cutting heats and friction heats were localized at the tool/workpiece interface, as a result, all data points of average surface roughness of the TECS was lower than that of the NTECS. Minimum average surface roughness of the machined surface obtained from the TECS was 16nm only, which is an encouraging result for UPM of difficult to cut materials. Considering the experimental results of both cutting force and chip formation, the possible reasons for generating enhanced surface roughness of the TECS are that decreases in cutting force variation and the level of material swelling by the use of the TEC device.

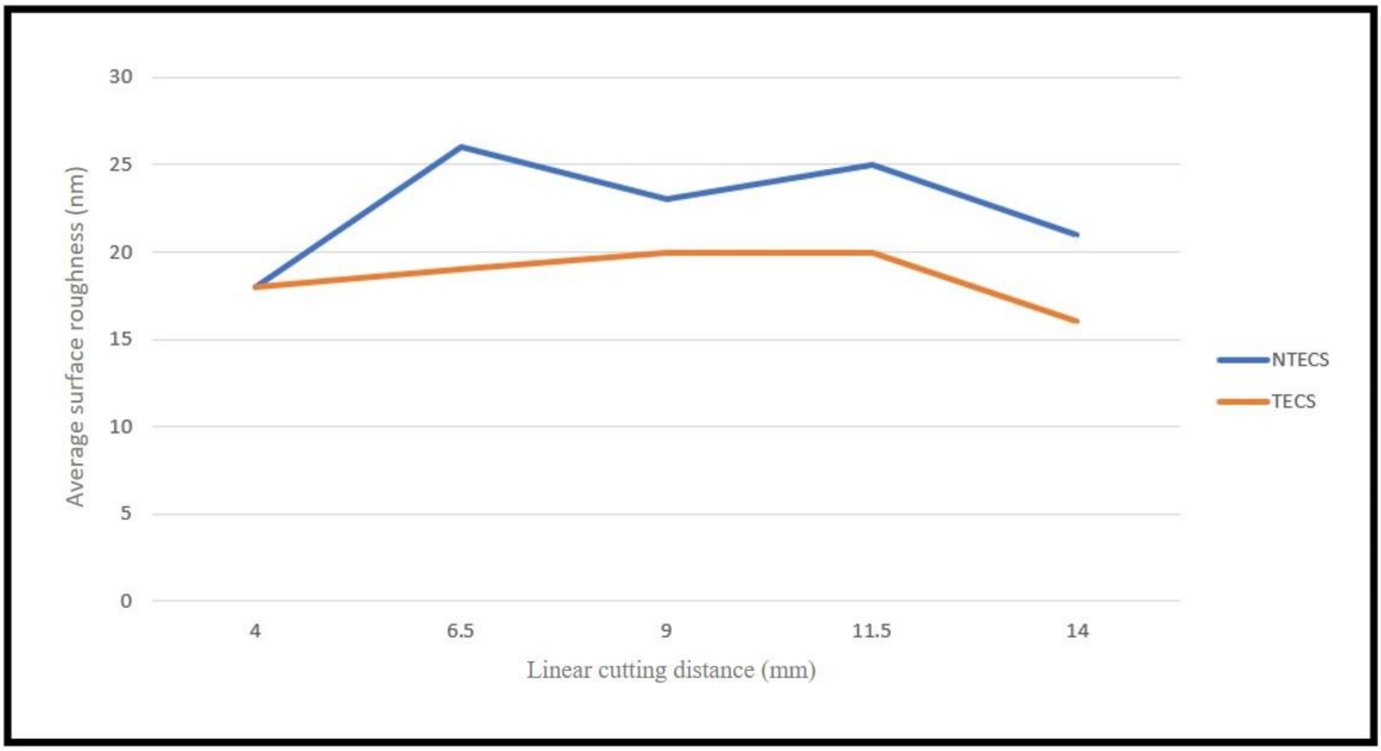


Figure 6. Average surface roughness of machined surface of TECS and NTECS

4. Conclusion

The application of TEC devices is spread on many industries to positively deliver heat dissipation for particular purposes. However, it has not yet been applied to the UPM area to provide effective cooling for lowering the problematic localised cutting heat at the machined surface, especially when machining low thermal conductivity alloys. In this study, a novel machining technology is proposed in the form of a TEC device for dissipating the high amount of cutting heat in UPM of titanium alloys. Under the cooling effect delivered from TEC fixture, the generation of long chip with smooth chip edge, the reduction of cutting force variation, and the improvement of the surface finish were achieved. This study reveals preliminary results of UPM using TEC fixture and provides an alternative approach to resolve the problematic high cutting heat in UPM of titanium alloys.

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Acknowledgment:

The work described in this paper was partially supported by a grant from General Research Fund from the Research Grants Council of Hong Kong Special Administrative Region under the project code PolyU 152125/18E, the National Science Foundation of China (NSFC) (Project no: 51675455).