Experimental investigation on the design of tool-bar combined the plastic layered laminates for vibration reduction in the precision turning process

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Abstract

The objective of this paper is to present the mathematical models to model and analyze the design of turning tool-bar combined the plastic layered laminates for minimizing the vibration amplitude of tool-tip in the precision turning process. The selected plastic materials are polyethylene（PE）and polyurethane（PU）. Machining parameters including the spindle speed, feed rate and cutting depth were chosen as numerical factor, and the status of plastic layered laminates was regarded as the categorical factor. The status of plastic layered laminates set up three categories including the solid tool （without plastic layered laminates）, tool with PE plastic layered laminates and tool with PU plastic layered laminates. An experimental plan of a four-factor's （three numerical plus one categorical） D-optimal design based on the response surface methodology （RSM） was employed to carry out the experimental study. Results show that the design of turning tool-bar combined the plastic layered laminates is proven to minimize the vibration amplitude of tool-tip, which leads to the results of the best machined surface. Using the tool with PE and the tool with PU in the same cutting conditions, the overall values of surface roughness represent the reduction of 4.32 and 14.34%, respectively, compared to the status of solid tool. According the experimental results, the design of turning tool-bar combined the PU plastic layered laminates have great improvement of the vibration-reduction.

Keywords: Vibration, Plastic, Roughness, Turning, Response surface methodology.

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使用刀把接合塑膠薄板的設計於精密車削過程中減少振動之實驗研究

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摘 要

本文目的是提出數學模式來建模與分析其使用刀把接合塑膠薄板的設計於精密車削過程中減少車刀振動的振幅。所選用的塑膠薄板是聚乙烯（PE）和聚氨酯（PU）。並對其加工參數如主軸轉速、進給率與切削深度等作為數值因素，塑膠薄板則作為類別因素。塑膠薄板的類別有三種類別，分別為實體刀把（沒有接合塑膠薄板）、刀把接合 PE 塑膠薄板與刀把接合 PU 塑膠薄板等。反應曲面法的 D-最佳設計法為本文實驗設計所採取用。其結果顯示為其使用刀把接合塑膠薄板的設計於精密車削過程中被証實可減少車刀振動的振幅，並有益於最好加工表面的結果。使用其刀把接合 PE 塑膠薄板與刀把接合 PU 塑膠薄板在相同加工條件狀況下，其表面粗糙度值分別降低 4.32 與 14.34%。並根據實驗結果，證實其刀把接合 PE 塑膠薄板的設計非常有益於減少車刀振動的振幅。

關鍵詞：振動、 塑膠、粗糙度、車削、反應曲面法。

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1. Introduction

In the metal cutting operations, the vibration conditions, occurring among the instrument, cutting tool, chuck and workpiece, play an important role in the machining performance characteristics of machined parts. Especially, the vibrations of cutting tool cause poor machined surface roughness, poor dimensional accuracy of the workpiece and abnormal tool wear or tool breakage, which lowers down the productivity and increases the cost of production. The appearance of vibrations of cutting tool is mainly subjected to the cutting dynamics process under various cutting conditions. The dynamic phenomena of cutting tool induced by the interaction of elastic system in the cutting process cause the relative displacement between tool and workpiece, which generates the vibration of cutting tool [1, 2]. Moreover, the major detrimental effect of vibration for the workpiece further worsens the quality of machined surface. Surface roughness is widely used in the index of a machined surface quality since a reasonably good surface finish is good for improving the tribological properties, fatigue strength, corrosion resistance and aesthetic appeal of the machined product [3, 4]. Excessive vibration can also interfere with the feed rate, cutting speed, and cutting depth.

In the past efforts, most researches reported in the literature focused on using virtual vibration signals to analyze the effects of cutting tool vibrations on the machined surface, and proposed the predicted vibrations model which are determined by the cutting process dynamics [5-10]. The amplitude and natural frequency of cutting tool vibrations under the resonance during cutting process are related to the dynamic cutting force and the chip-thickness variation acting on the cutting tool. The variation of cutting tool vibrations in the finish cutting process is observed through the monitor of surface roughness growth on the machined surface. Mer and Diniz [5] carried out the experiments for correlating the variation of the tool vibration, tool wear, tool life and surface roughness in the finish turning with the coated carbide tools. Thomas et al. [6] investigated the effect of cutting tool vibrations on surface roughness during lathe dry turning of mild carbon steel under different cutting parameters including the cutting speed, feed rate, cutting depth, tool nose radius, tool overhang and workpiece length. Jang et al. [7] proposed a measuring technique of online real-time roughness, which is a monitoring algorithm dealing with the relative cutting vibrations between tool and workpiece, so as to study the correlation between surface roughness and cutting vibration in hard turning process. Abouelatta and Madl [8] proposed the mathematical prediction model of surface roughness based on cutting parameters and tool vibrations in turning operations. Dimla [9] described a tool-wear monitoring procedure in a metal turning operation using vibration features. The monitoring procedure revealed that the vibration signals' features are related to the wear qualification of cutting tool-wear. Risbood et al. [10] utilized the fitted network for predicting the surface finish and dimensional deviation by measuring cutting forces and vibrations in the turning process. Consequently, the cutting tool vibrations had been reported to be much more significant than other monitoring signals [5–10] in predicting surface roughness.

Regarding with the control method of cutting tool vibrations, reported in the literature, basically involve either proper setup of cutting parameters [11] or stabilization of the relative displacement between tool and workpiece [12]. Tewani et al. [13] utilized the help of an active dynamic absorber to improve the cutting process stability of a boring bar for achieving the vibration control. Lee et al. [14] proposed the design of a dynamic vibration absorber to suppress vibrations in turning operations. Choudhury and Mathew [15] improved the location of inserts to promote the cutting process stability in the case of a milling operation.

In this study, an attempt had been made to minimize vibration amplitude of tool-tip using the plastic layered laminates, which provided in between the tool holder and turning tool-bar. The construction of turning tool-bar is designed to combine the plastic layered laminates for testing the effect of damping on the vibration-reduction. The selected plastic materials are polyethylene （PE） and polyurethane （PU）. A micro-cutting test with the diamond cutting tool is conducted to visualize the effect of tool-tip vibration on the performance of surface roughness. Diamond cutting tool is well known as a preferred tool for precision machining. The features of tool-tip vibration are extracted form the singular spectrum analysis （SSA）-processed vibration signals [16]. In this study, the spindle speed, feed rate and cutting depth were chosen as the numerical factor, and the selected plastic material was regarded as the categorical factor. A four-factor （three numerical plus one categorical） D-optimal design based on the response surface methodology （RSM） is employed to determine the experimental runs for the operating conditions of cutting process [17, 18]. The evaluation of machinability performances adopts the surface roughness to identify the quantitative estimation of tool-tip vibrations under the status of plastic layered laminates. In this paper, a mathematical model based on the RSM was proposed for modeling and analyzing the damping characteristics of plastic layered laminates on the surface roughness in the precision turning process using a diamond cutting tool.

2. Experimental design and procedure

2.1 Cutting too,l workpiece material and equipment

In this study, a series of micro-turning experiments using the diamond cutting tool were proposed to visualize the effect of tool-tip vibration on the performance of surface roughness. TNMN160408 polycrystalline diamond （PCD） tool inserts made by Diku Inc. were employed in the experiments. The cutting tool inserts was clamped onto a tool holder, type MTJNRL-2020K16; its major geometry is the working rake angle of 5°, the working side cutting edge angle of 60°, the tool flank angle of 6°, and the edge radius of 0.05 mm. The PCD tool inserts posses the characteristics of high thermal conductivity （700 W/mK）, high hardness （6,500~8,000 HV）, lower thermal expansion （1.45×10^{-6} 1/℃）, and lower friction coefficient （0.1～0.3）.

Although the diamond cutting tools reveal severe wear in the machining process of ferrous metals, the diamond cutting tools are widely used for the machining of various hardened non-ferrous materials in the manufacturing industry. Here, the workpiece material used in this study is the A6061-T6 aluminum alloy （ASTM B211 grade） with the following chemical compositions in mass%: 0.40 to 0.8 Si, 0.7 Fe max, 0.15 to 0.40Cu, 0.15 Mn max, 0.8 to 1.2 Mg, 0.04 to 0.35Cr, 0.25 Zn max, 0.15 Ti max and bal. Al. T6 temper 6061 aluminum alloy has an ultimate tensile strength of at least 290 MPa and yield strength of at least 241 MPa. Before cutting, the workpiece material was made into cylindrical bars with 40mm diameter and 100mm length. The metal cutting process was designed and machined by using Solidworks CAD/CAM software. The completion and positioning of cutting process were machined and controlled by using CNC software.

All the micro-turning experiments were conducted without any coolant in a Vcenter-55/70 CNC ultra-precision lathe, which have a maximum spindle speed of

4500 rpm, maximum turning diameter 260mm and a maximum power of 35 kW.

2.2 Plastic layered laminates

For the purpose of comparison and identification of damping effect induced by the plastic layered laminates, the polyethylene（PE）and polyurethane（PU）are selected as the material of plastic layered laminates. These materials usually used in the applications of vibration absorption such as the cushion of shock absorption in the structure. The samples of plastic layered laminates used in the experiments were cut sheets of the following dimensions: 50mm x 20mm x 1mm. The construction of turning tool-bar is designed to combine the plastic layered laminates, as shown in Fig. 1.

2.3 Experimental design

Figure 2 is a schematic diagram of the experimental setup. The monitoring system of cutting condition is composed of data acquisition system. The data acquisition system consists of two signal measurement sensors （accelerometer） and a singular spectrum analysis（SSA）device. In order to detect the vibration condition in the turning process, the vibration signals were measured using two 353B16 ICP accelerometers that was placed close to the tool and sensed the vibration in the transverse （ x-axis ） and longitudinal （ z-axis ） direction, respectively. The vibration signals along the cutting speed direction（transverse direction）was found to be highly sensitive to the performance of roughness on the machined surface. The sensitivity of the accelerometer was 10 mV/g（±15%）, and its measurement range was 0.7~20 kHz. These sensed vibration signals collected in the time domain were then sent to the SSA device for the calculation of root mean square （RMS） value of vibration signal for each experiment. The RMS value of vibration signal represents the square root of the average of the squared value of the vibration amplitude. Therefore, the vibration signals acquired through the accelerometer were processed by the SSA device for the analysis of frequency domain. SAA is a non-parametric technique of time series analysis based on principles of multivariate statistics. The procedure of SSA decomposes a given time series into a set of independent additive time series [16]. The main function of singular spectrum analyzer is to represent the spectrum characteristics of a given time series signal in the frequency domain. When the cutting operation is in process, the sensors dynamically collect the raw vibration signals. These vibration signals obtained in time domain are transformed to frequency domain by the Fast Fourier Transform （FFT）. The power spectrum density （PSD） analysis is performed according to the output of FFT. The vibration signals called spectrum in the frequency domain were analyzed for different cutting processes. In the experimental setup, the singular spectrum analyzer is a real-time spectrum analyzer （4 channel real time analyzer, G-Tech Instrument Inc.） which displays the singular amplitude of frequency domain immediately. The measured signal bandwidth was set within 3k Hz.

In the cutting process, the cutting length and diameter was kept the same so that no further vibrations are induced by the deflection of workpiece. The cutting length and diameter were fixed at 80 and 40 mm in the experimental design, respectively. In order to visualize the effect of tool-tip vibrations on the surface roughness, a micro-cutting test is conducted as follows. The spindle speed was varied from 2000 to 3000 rpm, the feed rates were changed between 0.02 and 0.10 mm/revolution, and the cutting depth was set from 0.04 to 0.12 mm. Table 1 shows the setting of experimental parameters and instrument under cutting A6061-T6 aluminum alloy in the precision turning process. According to the previous analysis in the real cutting process, the spindle speed （X_1）, the feed rate （X_2） and the depth of cut （X_3） were actually chosen as the three numerical factors for investigation. The status of rubber layered laminates （X_4） set up three categories including the solid tool （without rubber layered laminates）, tool with PE plastic layered laminate and tool with PU plastic layered laminate during the cutting process. The status of plastic layered laminates was regard as the categorical factor. Table 2 shows the controllable parameters and their levels in the coded and actual values.

In the present study, the frequency and amplitude of vibration signals were considered as the criterion and would affect the machinability evaluation in the precision turning process. The value of surface roughness here was adopted as the machinability evaluation of A6061-T6 machined in the precision turning process. The measurements of the surface roughness for the machined surface were performed by using a Mitutoyo SurfTest-402 with a cut-off length of 80mm and sampling length of 60mm. The maximum surface roughness （Rmax） was used to evaluate the surface roughness of the machined surface. The frequency and amplitude in the power spectrum density plots of the vibration signals were recorded to identify the quantitative estimation of cutting tool vibrations under various cutting conditions. The amplitude of vibration signals is conducted through collecting the “overall” vibration and plotting the vibration data in the time domain. The “overall” value can be quantified to record the total energy content of all vibration sources at all frequencies. In the precision turning process, the lower both amplitude of vibration signals and surface roughness （Rmax） are, the better the indication of the response characteristics. Those desired responses are regard as the smaller-the-better characteristics and influence each other relatively.

3. D-optimal design of the response surface methodology

A response surface-based D-optimal design was used to determine the experimental run for the operating conditions of cutting process. The procedures of D-optimal design consist of the defining level, selection of the fitting model and the chosen design points. The design points chosen from the set of candidate points depend on the selected model [17, 18]. As presented in Table 2, three numerical factors are varied over five levels, while one categorical factor is at three categories. In this study, the quantitative form of relationship between the desired response and independent input variables can be represented in the following:

$$Y = F(X_1, X_2, X_3, X_4) \qquad (1)$$

where Y is the desired response and F is the response function （or response surface）. In this particular case, the approximation of Y was proposed by using the fitted second order polynomial regression model which is called the quadratic model. The quadratic model was exactly suitable for studying carefully the interactive effects of combinative factors on the performance evaluations. The quadratic model of Y can be written as follows:

$$Y = a_0 + \sum_{i=1}^{4} a_i X_i + \sum_{i=1}^{4} a_{ii} X_i^2 + \sum_{i<j}^{4} a_{ij} X_i \qquad (2)$$

where a_0 is constant, a_i, a_{ii} and a_{ij} represent the coefficients of linear, quadratic and cross product terms, respectively. This model using the quadratic model of F in this study not only aims to investigate the response over the entire factor space, but also to locate the region of desired target where the response approaches to its optimum or near optimal value. In general, the quadratic model of desired response （Y） can be expressed as follows by matrix from as:

$$\mathbf{Y} = \mathbf{X}\boldsymbol{\alpha} + \boldsymbol{\varepsilon} \quad (3)$$

where $\mathbf{X}$ is a matrix of model terms evaluated at the data points, $\boldsymbol{\varepsilon}$ is an error vector. The unbiased estimator $\boldsymbol{\varepsilon}$ of the regression coefficient vector $\boldsymbol{\alpha}$ is estimated by using the least-squares error method as follows.

$$\boldsymbol{\alpha} = (\mathbf{X}^{\mathrm{T}}\mathbf{X})^{-1}\mathbf{X}^{\mathrm{T}}\mathbf{Y} \quad (4)$$

where is $\mathbf{X}^{\mathrm{T}}$ the transpose of the matrix $\mathbf{X}$.

The algorithm of D-optimal design for choosing design points is to select the set of design points by the selected quadratic model, which results in 18 minimum model points, and 5 points of them are used to estimate the lack-of-fit and replicates as well. The 28 experimental runs based on D-optimal design were performed to provide the suitable framework for this cutting experimentation, as shown in Table 3. It also displays the run numbers and the observed responses. Each cutting experiment was carried out two times at different time under the same conditions to ensure that the experimental data were repeatable.

4. Results and discussion

4.1 Identification of cutting tool vibration

In order to identify the machine-fixture-tool-work (MFTW) system dynamic parameters such as system damping and stiffness in stand still under various cutting conditions, the power spectrum plots and the vibration amplitudes in the longitudinal and transverse direction of the cutting tool under the no cutting condition were collected. These sensed vibration signals collected in the time and frequency domain were regarded as the basic reference to compare the quantitative estimation of cutting tool vibrations under various cutting conditions. Time domain signal analysis is essential to understand the overall vibration level generated in cutting process.

Figure 3 reveals the vibration amplitudes in the longitudinal and transverse direction of the cutting tool under the no cutting and dry cutting conditions. The dry cutting condition employs the cutting parameter setup of spindle speed of 2000 rpm, feed rate of 0.10 mm/rev and cutting depth of 0.12 mm. The vibration raw signals of longitudinal and transverse direction on the cutting tool were recorded within 150 ms. It shows that the amplitude of vibration signals under the cutting process is generally larger than under no cutting process. When the material of workpiece was cut, large amplitude vibrations induced by cutting force were generated on the cutting tool, especially in the transverse direction. The power spectrum plots of other vibration signals in the frequency domain under the no cutting and dry cutting conditions are presented in Fig. 4. The frequency bandwidth of vibration raw signals sets within 4 kHz. It is observed that the characteristics of the peaks appear at the frequency bandwidth within 0~1 kHz under the no cutting and dry cutting conditions. It was caused by the interaction between the tool-tip and the elastic recovery induced by the feed force of cutting tool. The vibration amplitudes of these peaks are found to be reinforced under the cutting conditions. These peaks present the status of the relative movement between cutting tool and workpiece, and are regarded as dominant factors affecting the surface roughness. But, the vibration amplitudes of the characteristic peaks at the high frequency bandwidth are found to be not very sensitive to the various cutting conditions.

4.2 The damping effects of plastic layered laminates

In order to understand the main features of the vibration raw signals using the cutting tool without/with the plastic layered laminates under the dry cutting conditions, the vibration amplitudes of longitudinal and transverse direction as described in Fig. 5（a） and 5（b）, respectively, are display in the time-domain. The status of plastic layered laminates combined the turning tool-bar in this study set up three categories including the solid tool （without plastic layered laminate）, tool with PE plastic layered laminate and tool with PU plastic layered laminate.

From Fig. 5（a）, it shows that the amplitude of vibration signals in the longitudinal direction using the tool with plastic layered laminates is generally smaller than with the solid tool. But in Fig. 5（b）, the value of transverse vibration amplitude is shown to greatly decrease using the tool with plastic layered laminates. This result has been attributed to the damping position of plastic layered laminates at the tip of cutting tool, which presents more and larger damping effects in the transverse direction. From the visualized time domain vibration data, the amplitude of vibration signals using the tool with PE and the tool with PU represent the reduction of 21.68 and 36.49%, respectively, compared to the solid tool in the transverse direction.

Figure 6（a） and 6（b） show the power spectrum plots of vibration signals using the cutting tool without/with the plastic layered laminates in the frequency domain. From Fig. 6（a）, it is observed that the vibration amplitude of the characteristic peaks appeared at the frequency within 0~2 kHz has not distinct variation in the longitudinal direction. The vibration amplitude of the characteristic peaks at the high frequency band is found to be not very sensitive to the status of plastic layered laminates. In addition, the difference of damping effect between the tool with PE and the tool with PU is not obvious in the longitudinal direction of cutting tool. From Fig. 6（b）, it shows that the vibration amplitude of the characteristic peaks appeared at the frequency within 0~1 kHz under the status of plastic layered laminates is smaller than under the status of solid tool. It also can be apparently seen that the vibration amplitude of the characteristic peaks are obviously minimized using the tool with plastic layered laminates. Consequently, the cutting tool with the plastic layered laminates can improve the damping forces of the turning tool-bar, and benefits to minimize the vibration amplitude, especially in the transverse direction.

4.3 Mathematical model of the surface roughness

The mathematical model of the surface roughness based on the RSM was proposed for analyzing the damping characteristics of plastic layered laminates in the precision turning process with the diamond cutting tool. In order to ensure the goodness of fit of the mathematical model obtained in this study, the test for significance of the regression model, the test for significance on individual model coefficients and the test for lack-of-fit need to be performed [17, 18] as shown Table 4. These tests are performed as analysis of variance （ANOVA） procedure by calculating the “F-value”, the “Prob. > F”, the determination coefficients （R2）, adjusted R-squared （R2 Adjusted） and the adequate precision （AP）. From the results of ANOVA, the values obtained were as follows: R2=0.9761, R2 Adjusted = 0.9354 and AP = 13.6122 for the surface roughness （Y_1）. Consequently, the obtained quadratic mathematical models for the surface roughness （Y_1） can be regarded as significant effect for fitting and predicting the experimental results and meantime the test of lack-of-fit also displays to be insignificant. Since each combination of categorical levels has a mathematical equation that predicts the response, three quadratic mathematical equations are presented for each status of plastic layered laminates. Using the results obtained in Table 4, it presents the final quadratic mathematical model of response equation in terms of actual factors as follows:

For the solid tool （without plastic layered laminate）

$$Rmax = -0.5049 + 0.0006N +3.0345f -4.6684\alpha_P -1.5\times10^{-7}N^2 +16.2711f^2 +12.8810\alpha_P^2 -0.00071Nf +0.0011N\alpha_P -9.2314f\alpha_P \quad (5)$$

For the tool with PE plastic layered laminate

$$Rmax = -0.7254 + 0.00076N +2.8169f -4.2338\alpha_P -1.5\times10^{-7}N^2 +16.2711f^2 +12.8810\alpha_P^2 -0.00071Nf +0.0011N\alpha_P -9.2314f\alpha_P \quad (6)$$

For the tool with PU plastic layered laminate

$$Rmax = -0.5898 + 0.00068N +3.3190f -4.2891\alpha_P -1.5\times10^{-7}N^2 +16.2711f^2 +12.8810\alpha_P^2 -0.00071Nf +0.0011N\alpha_P -9.2314f\alpha_P \quad (7)$$

Figure 7 displays the normal probability plot of the residuals for the values of surface roughness （Rmax, μm）. Notice that the residuals generally fall on a straight line implying that the errors are normally distributed. Furthermore, this supports adequacy of the least squares fit. It proves that the predicted values of surface roughness （Rmax, μm） are close to those readings recorded in the experiment with a 95% confidence interval.

4.4 The effect of the plastic layered laminates on the surface roughness

In the cutting process, the more stability of overall vibration in the tip of cutting tool leads to the results of the best machined surface and the continuous chip. According to the above developed mathematical model, the effect of plastic layered laminates on the surface roughness in the precision turning process had been analyzed. Figure 8（a）, 8（b） and 8（c） show the response surface and contour plot for the surface roughness Rmax in relation to the spindle speed （X_1） and feed rate （X_2） with the cutting depth （X_3） maintained at the middle levels under the status of plastic layered laminates. The values of surface roughness Rmax keep within 0.15~0.40, 0.14~0.39 and 0.10~0.37 μm, respectively, under the status of the solid tool, tool with PE plastic layered laminate, and tool with PU plastic layered laminate. The results of the analysis displayed in Fig. 8 clearly show that the value of surface roughness is shown decrease using the tool with plastic layered laminates. The overall values of surface roughness using the tool with PE and the tool with PU represent the reduction of 4.32 and 14.34%, respectively, compared to the status of solid tool in the same cutting conditions. This result has been attributed to the damping effects of plastic layered laminates at the tip of cutting tool, which presents the result of best machined surface.

The damping effect of plastic layered laminates on the surface roughness and vibration amplitude under the cutting conditions of level 1, level 3, and level 5, respectively, are displayed in Fig. 9（a）-（c）. As can be seen from these figures, the values of surface roughness are shown to decrease using the tool with plastic layered laminates. The damping effect of plastic layered laminates on the values of surface roughness presented in Fig. 9（a）-（c） shows that the change of surface roughness is identical to the results of Fig. 8. It also shows that this damping effect is able to reduce all the values of vibration amplitude in the longitudinal and transverse direction of the cutting tool. This event has been attributed to weaken the overall vibration, which causes the more stability of cutting process, and exhibits the result of best machined surface. The overall values of vibration amplitude in the longitudinal direction using the tool with PE and the tool with PU approximately display the reduction of 2.17 and 3.15%, respectively, compared to the status of solid tool in the same cutting conditions. For the overall values of transverse vibration amplitude using the tool with PE and the tool with PE, the reduction presents 5.10 and 10.56%, respectively. Consequently, the design of turning tool-bar combined the plastic layered laminates is beneficial to minimize the vibration amplitude in the longitudinal and transverse direction of the cutting tool. Therefore, the best surface roughness is achieved using the tool with plastic layered laminates as expected. The design of turning tool-bar combined the PU plastic layered laminates proved to have great improvement of the vibration-reduction.

5. Conclusions

This paper developed and analyzed the design of tool-bar combined the plastic layered laminates for vibration reduction in the precision turning process. D-optimal design based on the RSM was employed to carry out the experimental study. According to the developed mathematical model, the damping characteristics of plastic layered laminates on the surface roughness in the precision turning process has been analyzed and draws the following conclusions:

(1) The results of ANOVA and comparisons of experimental data represent that the mathematical model of the value of surface roughness proposed in this study is fairly well fitted with the experimental values with a 95% confidence interval.

(2) Using the tool with PE and the tool with PU in the same cutting conditions, the overall values of surface roughness represent the reduction of 4.32 and 14.34%, respectively, compared to the status of solid tool.

(3) The design of turning tool-bar combined the plastic layered laminates is proven to minimize the vibration amplitude of tool-tip. For the overall values of transverse vibration amplitude using the tool with PE and the tool with PE, the reduction presents 5.10 and 10.56%, respectively.

(4) Compare the PE and the PU on the vibration-reduction, and the design of turning tool-bar combined the PU plastic layered laminates proved to have great improvement of the vibration-reduction.

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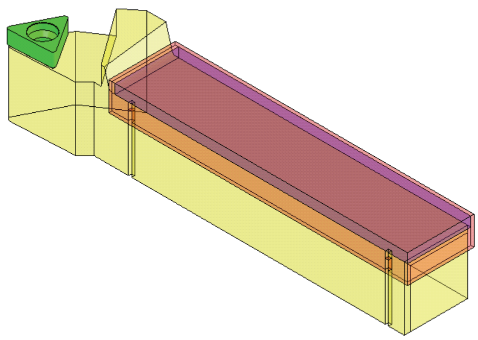
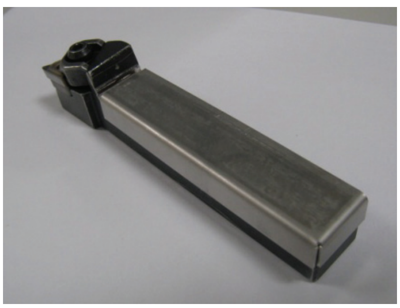
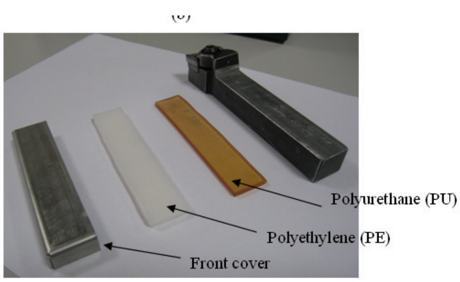


（a）



（b）



（c）

Fig. 1 The design of turning tool-bar: （a） the CAD's sketch, （b） the tool with plastic layered laminates, and （c） the components.

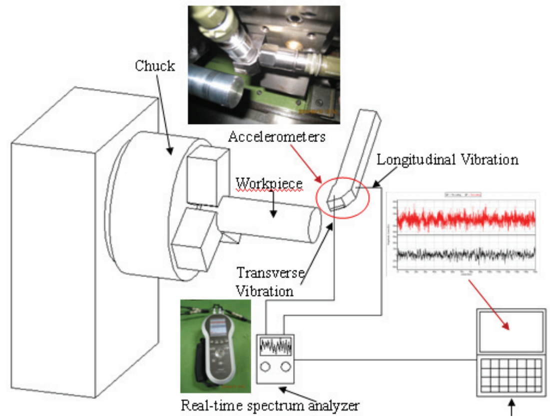
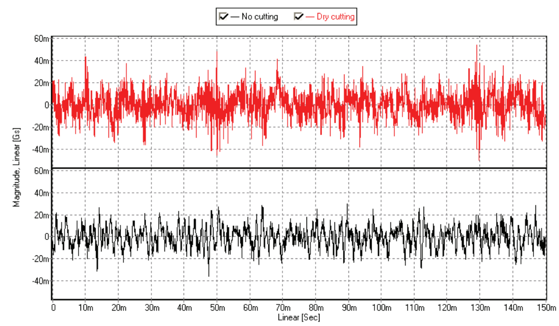
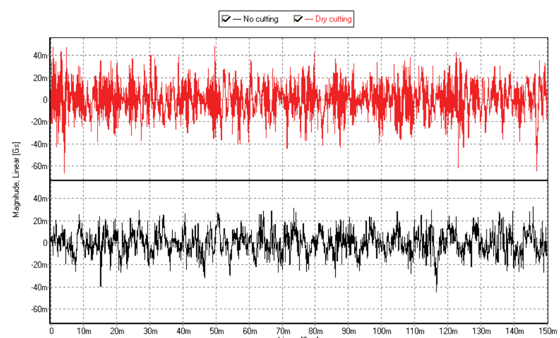


Fig. 2 Schematic diagram of the experimental setup.

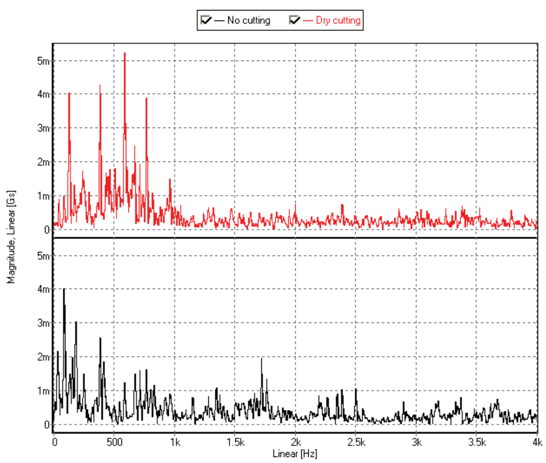


（a）

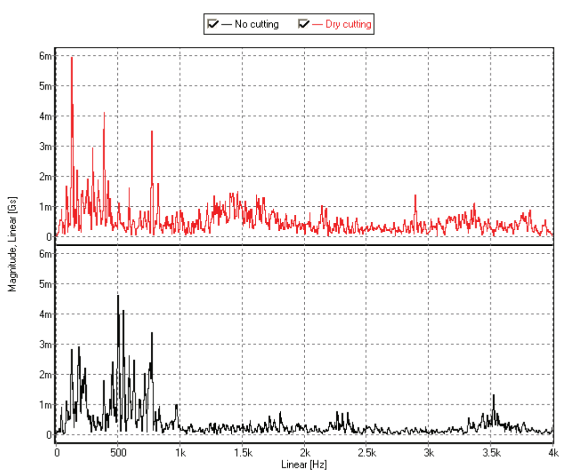


（b）

Fig. 3 The vibration amplitude of (a) longitudinal and (b) transverse direction on the cutting tool under the no cutting and dry cutting conditions (Red : No cutting, Black : Dry cutting).

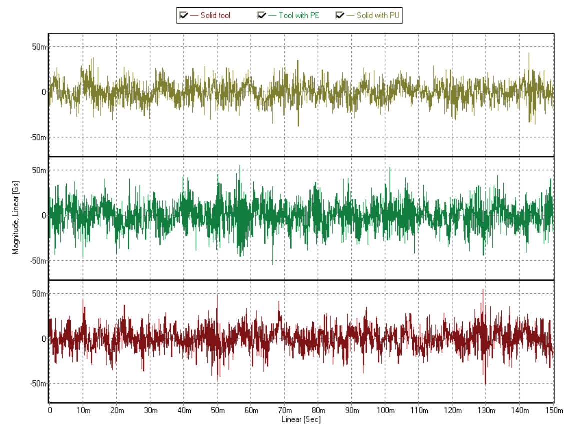


(a)

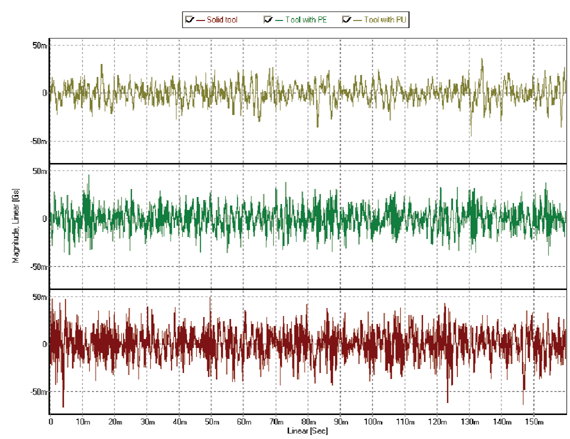


(b)

Fig. 4 The power spectrum of (a) longitudinal and (b) transverse direction on the cutting tool under the no cutting and dry cutting conditions. (Red : No cutting, Black : Dry cutting)

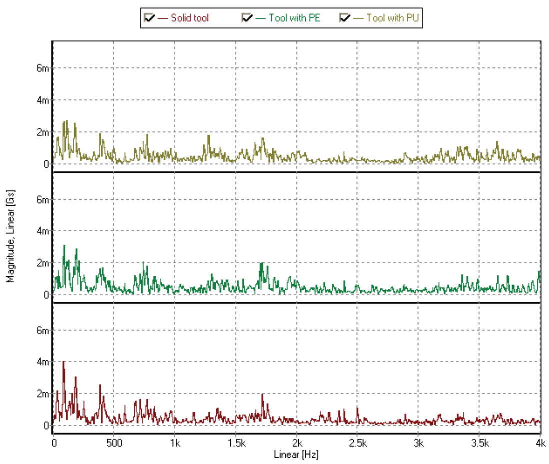


(a)

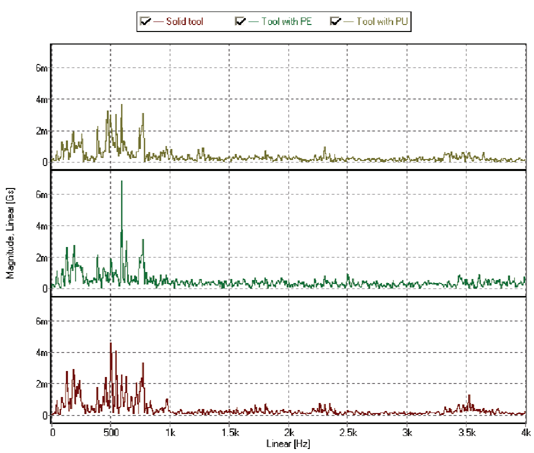


(b)

Fig.5 The vibration amplitude of （a） longitudinal direction and （b） transverse direction on the cutting tool without/with the rubber layered laminates under the dry cutting conditions.（Yellow : Solid tool, Green : Tool with PE, Brown : Tool with PU）



（a）



（b）

Fig.6 The power spectrum of（a） longitudinal direction and （b） longitudinal direction on the cutting tool without/with the plastic layered laminates under the dry cutting conditions. （Yellow : Solid tool, Green : Tool with PE, Brown : Tool with PU）

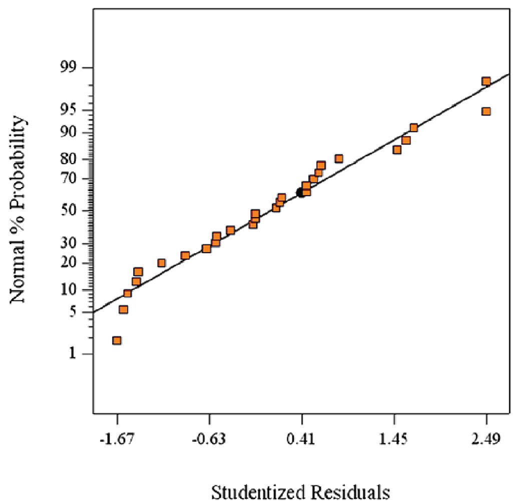
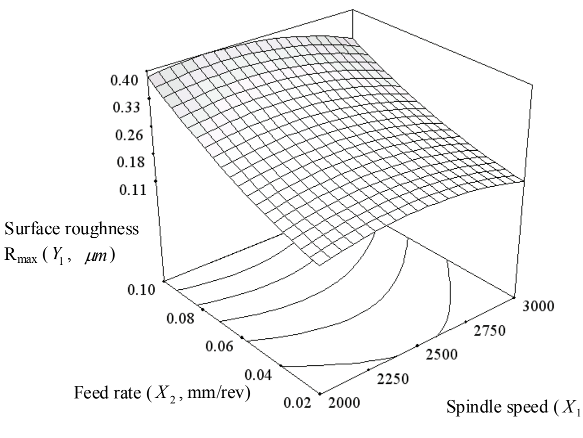
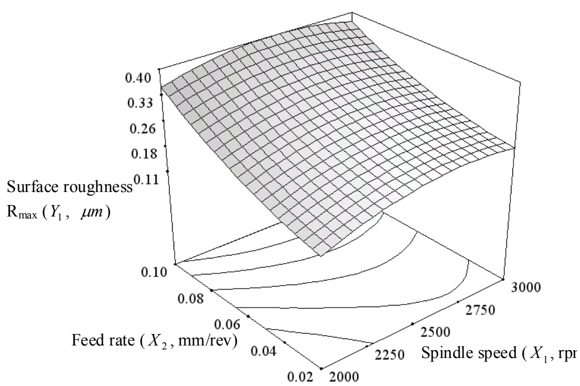


Fig. 7 The Normal probability plot of residuals for the surface roughness （Rmax, μm ）.

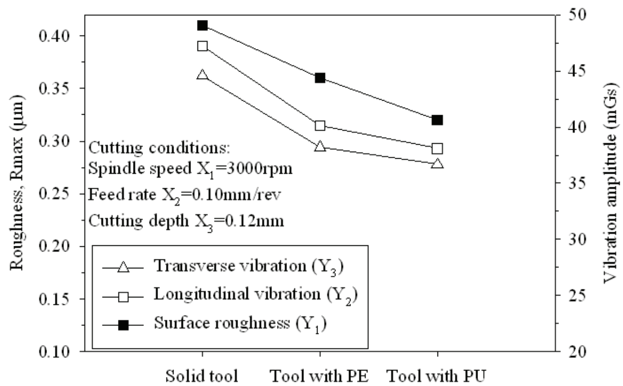


（a）

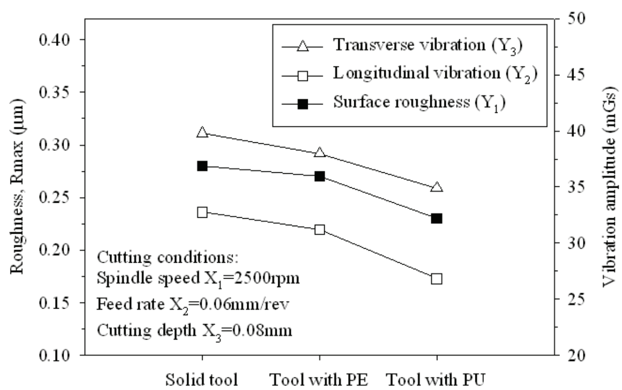


（b）

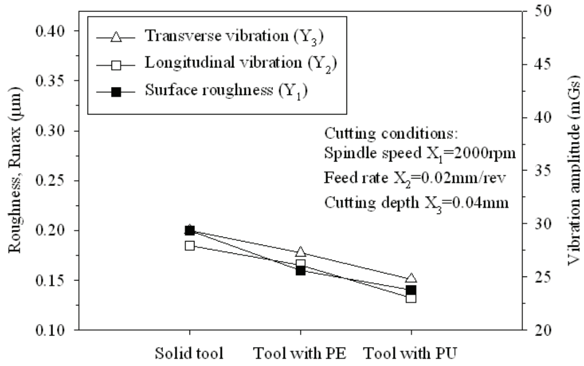
Fig. 8 The response surface and contour plot for the surface roughness Rmax under the status of （a） the solid tool, （b） tool with PE plastic layered laminate, and （b） tool with PU plastic layered laminate.



（a）



（b）



（c）

Fig. 9 The effect of the rubber layered laminates on the surface roughness and vibration amplitude under the cutting conditions of （a） level 1, （b） level 3, and （c） level 5.

Table 1 Experimental parameters and instrument

Working conditions	Unit	Description
Lathe		Vcenter-55/70 CNC
Workpiece		A6061-T6
Holder type		MTJNRL-01
Insert type		TNMN160408 polycrystalline diamond （PCD）
Cutting length	mm	80
Cutting diameter	mm	40
Spindle speed	rpm	2000 – 3000
Feed rates	mm/rev	0.02 – 0.10
Cutting depth	mm	0.04 – 0.12
Rubber layered laminates		Polyethylene （PE）, Polyurethane （PU）
Accelerometers		353B16 ICP
Data acquisition		Real-time spectrum analyzer

Table 2 Design schema of machining parameters and their levels

Parameters	Code		Levels				
			1	2	3	4	5
		Numerical	– 2	– 1	0	+1	+2
		Categorical	1	2	3		
Spindle speed （rpm）	X_1		2000	2250	2500	2750	3000
Feed rate （mm/rev）	X_2		0.02	0.04	0.06	0.08	0.10
Cutting depth （mm）	X_3		0.04	0.06	0.08	0.10	0.12
Plastic layered laminates	X_4		Solid tool	Tool with PE	Tool with PU		

Table 3　Design layout and experimental results

Run	Numerical factor			Categorical factor	Responses		
	Spindle speed（ rpm）	Feed rate（mm/rev）	Cutting depth（mm）	Plastic layered laminates	Roughness	Vibration amplitude	
	X_1	X_2	X_3	X_4	R_{max}（Y_1，μm）	Longitudinal（Y_2,mGs）	Transverse（Y_3,mGs）
1	2000	0.1	0.12	PE	0.32	40.79	41.47
2	2500	0.02	0.12	PU	0.18	18.54	37.23
3	3000	0.1	0.12	Solid tool	0.34	37.99	37.60
4	2000	0.02	0.12	Solid tool	0.16	18.56	21.67
5	2000	0.1	0.12	PE	0.35	41.61	43.39
6	3000	0.02	0.08	Solid tool	0.14	15.55	22.63
7	2000	0.1	0.08	Solid tool	0.38	42.55	43.06
8	2500	0.06	0.08	PE	0.26	30.94	38.63
9	2000	0.02	0.08	PE	0.14	18.50	20.42
10	3000	0.02	0.04	PE	0.17	24.61	23.95
11	2000	0.1	0.08	Solid tool	0.39	45.82	51.31
12	2500	0.04	0.06	Solid tool	0.26	26.57	34.63
13	2750	0.04	0.08	PU	0.18	25.76	34.50
14	2000	0.02	0.08	PE	0.15	23.04	25.03
15	2000	0.02	0.04	Solid tool	0.19	28.12	32.50
16	3000	0.02	0.04	PE	0.21	21.66	27.75
17	3000	0.1	0.08	PE	0.38	40.98	45.35
18	3000	0.06	0.12	PU	0.2	26.68	22.86
19	3000	0.1	0.04	Solid tool	0.34	43.23	43.52
20	3000	0.1	0.08	PE	0.37	40.47	42.97
21	3000	0.06	0.04	PU	0.19	19.88	21.18
22	2500	0.1	0.12	PU	0.4	40.90	51.27
23	2000	0.06	0.12	PU	0.22	22.74	37.10
24	2000	0.02	0.04	PU	0.14	22.68	22.10
25	2000	0.1	0.04	PE	0.42	53.04	59.42

26	2500	0.1	0.04	PU	0.38	51.88	58.07
27	3000	0.02	0.12	PE	0.3	38.04	38.58
28	2250	0.06	0.06	PU	0.23	30.93	33.93

Table 4 Results of the ANOVA

Source	Sum of Squares	Degrees of freedom	Mean Square	F-Value	Prob. > F	
Model	0.2889	17	0.0142	24.0284	< 0.0001	significant
Residual	0.0059	10	5.9182E-4			
Lack of Fit	0.0045	5	9.0364E-4	3.2272	0.1122	not significant
Pure Error	0.0014	5	0.00028			
Cor. Total	0.2476	27				

Standard. Deviation= 0.0243	R^2= 0.9761
Mean= 0.2639	R^2 Adjusted=0.9354
Coefficient of variation= 9.2174	Predicted R^2= 0.3647
Predicted residual error of sum of squares （PRESS） = 0.1573	Adequate precision （AP） =13.6122