Online measurement of the elastic recovery value of machined surface in milling titanium alloy

Panling Huang · Jun Zhou · Liang Xu

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Abstract
This paper aimed to obtain the elastic recovery value of the machined surface of the workpiece in the milling process of titanium alloy, because it can cause strong friction between the tool flank and the workpiece surface. A new online measurement system was designed to monitor the elastic recovery behavior of Ti6Al4V alloy in dry milling based on the digital image correlation (DIC). DIC measurement principle was intuitively analyzed by means of picture illustration. The orthogonal milling experiments were designed with different cutting parameters and the experiment processes were designed in detail, including the installation of DIC measurement system, the speckle disposal of the measured surface and the field calibration of test instrument. The displacement curve of the target region was analyzed according to the material deformation characteristics of metal materials in the cutting process and thus the calculation method of elastic recovery value of machined surface was obtained. Besides, the optimization method of cutting parameters with the minimum elastic recovery value in titanium alloy milling was also obtained, which can be expanded to the machining measurement of other difficult-to-machine materials.

Keywords Titanium alloy · Elastic recovery · DIC · Non-contact sensor

1 Introduction
Titanium alloys have been widely used in aerospace industry and other fields owing to their high specific strength, good stability at high temperatures, high resistance to fatigue and creep, excellent corrosion resistance and so on [1]. Titanium alloys are mainly used in aircraft engine compressor parts, followed by rocket, missile and high-speed aircraft structural part. Therefore, the machining of titanium alloy needs a large amount of material removal rate and good surface quality. However, titanium alloys are regarded as one of difficult-to-machining materials because of the following characteristics [2, 3], as shown in Fig. 1, making it urgent to carry out high-efficiency and high-quality titanium alloy machining research.

1. Low thermal conductivity
   Thermal conductivity of titanium alloy material is very low, and thus, it is difficult to dissipate the heat generated during machining from the cutting zone [4, 5]. This, in turn, will result in higher temperature of tool and lose of its mechanical strength and hardness, and eventually shorten tool life [6].

2. Lower elastic modulus $E_0$ [7, 8]
   Because of the lower elastic modulus and high yield strength, the volume of workpiece material in the vicinity of the machined surface will undergo excessive elastic deformation during machining. Therefore, it is readily not only to cause the dimensional error of machined parts, but also cause severe friction between tool flank and workpiece, which subsequently led to tool wear and poor surface quality.

3. Higher work hardening
   When machining titanium alloy, work hardening is serious, which is easy to cause tool wear and even edge collapse, and the machining surface quality is difficult to ensure.

4. Small deformation coefficient
   The deformation coefficient of titanium alloy is typically very small, which greatly increases the distance of chip sliding friction on the front tool surface of the tool and accelerates the tool wear. At the same time, the
temperature of the tool will increase due to the friction of the chip during walking on the rake face.

5. High chemical activity [9].

Titanium alloys have high chemical activity especially under high temperature. During machining, it is easy to generate strong adhesion of workpiece material over the tool edge [10, 11], and react easily with oxygen in the air to accelerate tool wear, thus leading to edge breakage [12].

Collectively, the above-mentioned five unique and inherent characteristics of titanium alloys largely contribute to the poor machinability [13]. Rapid tool wear and poor machined surface quality are the main factors in restricting the efficient machining of titanium alloy. Active chemical reactivity, severe friction and elastic recovery of the machined surface are other factors to cause poor machinability of titanium alloy, and these factors are interlinked each other. For example, high cutting temperature will promote the chemical reaction and decreases the elastic modulus of titanium alloys [14]. In addition, the cutting vibration caused by sawtooth chip during machining will also lead to poor machinability of titanium alloy. All these characteristics have severely limited high-speed cutting of titanium alloy, making it urgent to improve the machinability of titanium alloy. To this end, Many studies are primarily focused on the research about the improvement on machinability of titanium alloy, which mainly covers the following aspects.

Rational selection of tool base and coating materials has been validated to be an effective way to reduce the diffusion and chemical reaction between the tool and the workpiece [15]. Commercially available WC–Co carbide is regarded as the most suitable tool material for the machining of titanium alloys [16, 17]. However, WC–Co tools wear rapidly in machining titanium alloys, particularly at high cutting speed [18]. So far, most of the carbide tools are coated with CVD (chemical vapor deposition) or PVD (physical vapor deposition) hard coatings to resist tools wear [19, 20], and CVD diamond-coated carbide tools represents a promising choice for machining titanium alloys [21]. Optimization of tool structure and cutting parameters can effectively improve the machinability of titanium alloy [22]. The tool structure has a considerable influence on the machined surface integrity [23]. It is proposed to use non-standard tool, namely, variable pitch tool, to reduce cutting vibration by destroying regeneration effect [24], correspondingly decrease cutting temperature and
tool wear. Stability lobe diagram that is plotted between spindle speed and depth of cut is often used to select the proper cutting parameters to avoid cutting chatter [25, 26]. Cutting fluids has been traditionally used to reduce the temperature generated during machining and improve the tool life [27]. However, it has many adverse effects including but not limited to environmental pollution and potential danger to operators owing to the excessive usage of cooling/lubricating fluids [28]. Moreover, it is expensive and time-consuming to preservation, maintenance and process such spent fluids, which greatly increases the total manufacturing cost [29]. Thereafter, various cooling and lubrication techniques in the cutting zone have been successively developed, such as MQL (minimum quantity lubrication) [30], cryogenic machining [31], and HPC (high-pressure cooling) [32]. Dry machining that can eliminate cutting fluids is therefore considered an environmentally friendly and sustainable machining strategy [33].

It can be seen from the previous studies that although the elastic recovery of titanium alloy during machining is relatively high, scanty attention has been paid to its measurement. The main reason probably lies in the complexity of titanium alloy cutting environment, especially the micro scale. There were some studies, though, have partially mentioned this issue; for instance, Zhao et al. [34] have developed the material constitutive models and geometrical relationships about Ti6Al4V alloy to estimate the temperature evolution, cutting forces, internal force/stress distribution, and the spring back variation during micro groove turning. From theoretical and experimental analysis, we may reasonably conclude that more than 45% of the thrust comes from the spring back. Additionally, Schaal et al. [35] have designed an online measuring system for the elastic recovery of turning aluminum alloy and titanium alloy. This elastic recovery measuring system contains three non-contact capacitive sensors: the first and second sensors were fixed on machine, and the third sensor was fixed on the tool holder. The elastic recovery values were calculated using the relationship among the values measured by three sensors. However, the measurement system might inevitably produce measurement deviations due to the influence of installation accuracy, tool vibration, and surface roughness difference before and after the cut. Hence, it is necessary to develop new high-precision measurement methods.

In this work, we have developed a novel online measurement of elastic recovery of the machined surface in dry milling titanium alloys based on DIC technique. The purpose of this study is to reveal the variation of elastic recovery of the machined surface of titanium alloy, and provide theoretical guidance for optimizing the micro structure of tool flank to suppress the vibration caused by the elastic recovery of the machined surface.

DIC technology is a kind of non-contact modern optical measurement experiment technology. It has been widely used in materials science, electronic packaging, bio-medicine, manufacturing, and other scientific and engineering fields due to its simple optical path, good environmental adaptability, wide measurement range, and high degree of automation welding and many other favorable features [36]. The most extensive and mature application of DIC technology in material field is used to measure the real-time strain of the sample in the tensile process [37]. Following are some typical examples. Wu et al. have used the 2D-DIC technique to monitor the full/local field strain in both coating and substrate systems [38]; Zhu et al. introduced the 3D-DIC as a non-destructive full-field optical measurement technique to reconstruct and mapped the out-of-plane displacement of the deformed coating surface [39]. While Li et al. carried out the fracture analysis of concrete to ensure the relative position of the camera and the specimen plane by 3D-DIC technology [40].

By means of the measurement advantages of DIC, we have developed an online measuring system of the elastic recovery of the machined surface in milling titanium alloy based on PMLAB DIC-3D software. The measurement principle of DIC and multi-factor orthogonal experiments to measure the elastic recovery of the machined surface was introduced in Sect. 2. In Sect. 3, experiment processes and results were presented. Finally, the conclusions were given in Sect. 4.

## 2 Online measurement of the elastic recovery of machined surface

Considering the elastic recovery of the machined surface belongs to microscale together with the poor cutting environment, it is not suitable for direct contact measurement. Thereby, in the present study, DIC optical non-contact method was utilized to measure the elastic recovery.

### 2.1 DIC measurement principle

According to the measurement principle of DIC, two cameras was employed to capture the speckle image of object surface from different angles to match the overlapping areas in the images taken by the two cameras. Meanwhile, camera calibration parameters were used to determine the three-dimensional coordinates of each point on the object surface in the overlapping area, aiming to realize the three-dimensional morphology and deformation measurement. Figure 2a shows the tested part before deformation, while Fig. 2b displays the tested part after deformation under the action of load \( P \). The corresponding speckle image was defined as the reference subset and the target subset. Based
on the measurement method of DIC, a correlation between two images taken before and after loading the tested part was established, and the displacement distribution of the whole tested part in the discrete space was finally calculated.

### 2.2 Experimental conditions and procedures

Figure 3a, b demonstrate the schematic picture and actual pictures of the experiment setup, respectively. The dry milling experiments were conducted on a vertical machining center of DAEWOO company (ACE-V500). The workpiece material is Ti6Al4V alloy, and the shape of the workpiece is a cuboid block with a size of 70 (length) × 40 (width) × 30 (height) mm. A new carbide end mill with an AlCrN coating was selected, and its geometric parameters are listed as follows: tooth number $N$ is 4, diameter $D$ is 20 mm, overhang length $l$ is 42 mm and helix angle $\beta$ is 38°.

PMLAB DIC-3D was used to monitor the elastic recovery of machined surface. The measuring system includes a non-contact 3D displacement measurement software, a PM-G universal measuring head that contains two industrial cameras and an integrated polarization light source. FLIR industrial cameras are selected with the resolution of 2736 × 2182 and maximum acquisition frequency of 13 fps. KOWA industrial lens has an aperture of 2.0, a focal length of 28 mm, and an aperture of 1.3 inch. Measurement range of the system: large field of view $> 1 \text{ m} \times 1 \text{ m}$, and maximum measurement points of 20,000.

The speckle image of the object surface is shown in Fig. 3c. Before painting, it is necessary to ensure that the surface of the test part was smooth enough and free from oil stains to make sure that the sprayed paint can firmly adhere to the workpiece surface. Firstly, spray a layer of matte white primer on the surface of parts as required, and then spray black spots. Generally speaking, a point is required to occupy 4–6 image pixels.
After installing all the experimental devices, the test sites must be calibrated as shown in Fig. 4. The calibration process is exhibited as follows.

Firstly, open the camera cover and put the camera in a suitable position to make sure the size of the object is approximately same in the two cameras. Then, fix the two cameras and adjust the focus so that the image can be clearly displayed. After that, the camera cannot be moved or the focal length cannot be adjusted during the whole processes of calibration and related calculation. The front calibration area of the calibration plate is a circular array of 12 columns and 9 rows, in which there are three direction identification points. During calibration, keep the front face of the calibration plate as parallel as possible to the measuring surface, and place it in front of it. Collect 12 groups of calibration drawings. The calibration plate in each drawing should be at different positions and angles, but it needs to be parallel to the speckle surface as far as possible.

After calibration, turn on the camera and select binocular camera for acquisition. The acquisition time is 150 s, and the time interval of each photo is 0.2S. According to the calibration data and the collected data, the displacement of pixel sub area is calculated and analyzed.

### 2.3 Cutting system and cutting parameters

To investigate the influences of milling parameters on the elastic recovery of Ti6Al4V alloy during dry milling, multi-factor orthogonal design method was employed in this experiment. The DIC measuring device is clamped on the workbench to reduce the influence of the vibration of the machine tool. The camera is mounted 1000 ~ 1500 mm from

| Factor | n (r/min) | ap (mm) | f (mm/min) |
|--------|-----------|---------|------------|
| 1      | 400       | 1       | 30         |
| 2      | 600       | 1.5     | 40         |
| 3      | 800       | 2       | 50         |
| 4      | 1000      | 2.5     | 60         |

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Fig. 4 The test site calibration

Fig. 5 Real time displacement change

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Table 1 Factors and levels of orthogonal test
the surface of the workpiece to ensure that the chip does not splash the camera lens. According to the conditions of the experimental equipment and the convenience of the measurement process, the radial cutting depth is usually designed to be about 30% of the cutter diameter, so that it can be fixed as 6 mm in all tests. The orthogonal table is shown in Table 1 to set the other cutting parameters. The three factors in the experiment are the spindle speed \( n \), feed rate \( f \), and axial cutting depth \( a_p \). All tests are conducted under dry milling conditions.

### 3 Experiment procedures and results

In titanium alloy milling, the spatial position of the target subset will change with the feed motion of the tool. In order to extract the elastic recovery value of machined surface in titanium alloy milling process, it is necessary to analyze the whole cutting process and the position change curve of the target subset.

#### 3.1 Experiment section

As displayed in Fig. 5, during milling process of Ti6Al4V alloy, the target subset below the axial cutting depth is selected as the monitoring region to read the displacement data taken from industrial cameras, image acquisition and image processor. The subset selection criteria is that it is relatively close to the machined surface so as to reflect the elastic recovery value of the machined surface more accurately.

Figure 5a shows the schematic diagram of different cutting positions of the tool and the deformation of the target subset of the tested part. Figure 5b exhibits the y-direction displacement curve of the target subset obtained by the measurement system with the change of cutting time. The abscissa is the milling time, and the

Table 2 Measured values under different cutting conditions

| Number | \( n \) | \( a_p \) | \( f \) | \( \delta \) (um) | Number | \( n \) | \( a_p \) | \( f \) | \( \delta \) (um) |
|--------|--------|--------|--------|-------------|--------|--------|--------|--------|-------------|
| No. 1  | 400    | 1      | 30     | 2.69        | No. 9  | 800    | 2      | 30     | 5.12        |
| No. 2  | 400    | 1.5    | 40     | 3.12        | No. 10 | 800    | 2.5    | 40     | 5.32        |
| No. 3  | 400    | 2      | 50     | 3.64        | No. 11 | 800    | 1      | 50     | 4.64        |
| No. 4  | 400    | 2.5    | 60     | 3.98        | No. 12 | 800    | 1.5    | 60     | 4.84        |
| No. 5  | 600    | 1.5    | 30     | 3.35        | No. 13 | 1000   | 2.5    | 30     | 5.46        |
| No. 6  | 600    | 2      | 40     | 3.64        | No. 14 | 1000   | 1      | 40     | 4.68        |
| No. 7  | 600    | 2.5    | 50     | 4.08        | No. 15 | 1000   | 1.5    | 50     | 4.89        |
| No. 8  | 600    | 1      | 60     | 3.28        | No. 16 | 1000   | 2      | 60     | 5.33        |
ordinate is the displacement in y-direction of the target subset. The cutting time of the tool is 147.8 s.

When the tool passes through the top of the target subset for about 8 s, the milling is stopped and the tool is lifted to complete the data collection. Because of the homogenization change of titanium alloy materials, the displacement change of the target subregion is equal to that of the machined surface. In the process of the tool feed process, the cutting load $P$ is gradually getting closed to the target subset; the displacement curve shows a downward trend. A negative sign indicated that the displacement of the machined surface changes downward, and the greater the absolute value is, the greater the displacement occurred.

As shown in Fig. 5c, affected by cutting force and cutting vibration, the whole curve has some fluctuation. Specifically when the tool passes over the target subset, the displacement of the target sub-region first decreases under cutting load. When the tool leaves, due to the elastic recovery of the material, the displacement of the target subset appears a rising trend. The difference of the two average displacements between the descending process and the rising process is defined as the elastic recovery value of the machined surface. Herein, it is represented by the letter $\delta$. Reading time of the elastic recovery value is set to 140–148 s.

3.2 Results

Figure 6 shows the y-direction displacement curve of 16 group experiments within the given 8 s. It can be seen from each group of data, the compression of the target subset materials occurred as the load reaches and the elastic recovery trend when the load leaves.

Based on the above calculation method, the elastic recovery value of the machined surface under the corresponding cutting conditions is as shown in Table 2. Further range analysis is shown in Fig. 7.

From Fig. 7a, the elastic recovery value of machined surface increases as three factors increase. The spindle speed has the greatest influence on the value, and the feed per tooth has the least influence. This might be because that higher spindle speed may increase the cutting temperature and reduce the elastic modulus of the material, and eventually leading to increase the elastic recovery value. Larger axial cutting depth can increase the cutting force load, which leads to larger elastic recovery value.

Figure 7b shows the difference between the maximum value and minimum value of the elastic recovery value under the condition of three factors. The difference values of the three factors are 1.7325, 0.8875, and 0.2025 $\mu$m, respectively. Therefore, from reducing the elastic recovery value, value point of view, to increase the material removal rate (such as rough machining), the feed rate per tooth can be consider to increase, and then the axial cutting depth.

Evidence has evinced that in the process of micro groove cutting of Ti6Al4V alloy, the elastic recovery is in the range of 0.9–1.1 $\mu$m [35]. While other study displayed that when the cutting parameters of Ti6Al4V alloy are set to, cutting depth $a_p = 0.05$ mm, feed rate $f = 0.1$ mm/rec, cutting speed $v = 10–450$ m/min, and the elastic recovery values are in the range of 0.3–1.6 $\mu$m with a sharp tool (cutting edge radius 12 $\mu$m), while the values are in the range of 2.1–9.6 $\mu$m with a blunt tool (cutting edge radius 72 $\mu$m) [36]. In this paper, the values are in the range of 2.69–5.46 $\mu$m during milling Ti6Al4V alloy.

4 Conclusion

In this paper, the orthogonal experiment of titanium alloy in dry milling was rationally designed, and the elastic recovery displacement for the machined surface of workpiece was measured online by DIC non-contact sensor. The main conclusions were drawn as follows:

1. The principle of DIC non-contact sensor for measuring the elastic recovery of machined surface of workpiece was analyzed. Because of the homogeneity of workpiece material, the displacement change of the target subset is equivalent to the elastic recovery displacement of the machined surface of workpiece. Thus, the feasibility of online measurement of the elastic recovery displacement of non-contact sensor is proved.
2. The orthogonal experiment of titanium alloy in dry milling was designed. The DIC non-contact sensor measuring device was installed on the workbench to synchronize the vibration of the machine tool, so as to avoid the measurement error caused by the vibration. The curve change of the displacement change of the target sub-region in the whole milling process was analyzed, and the calculation data and method of the elastic recovery value are obtained after analysis.

3. Through the range analysis of the experiments, it is concluded that from the perspective of reducing the elastic recovery value of the machined surface, in the milling process of titanium alloy, large removal of materials such as rough machining can be realized by increasing the feed per tooth, and secondly by increasing the axial cutting depth. Increasing the rotating speed to improve the material removal rate will cause a great material elastic recovery, resulting in the acceleration of tool wear.

Author contribution All authors took part in the work. Panling Huang — conceptualization, data processing, original draft, validation. Jun Zhou — supervise, project administration, funding acquisition. Liang Xu — experiment, data collection, original draft.

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Declarations

Conflict of interest The authors declare no competing interests.

References

1. Arrazola PJ, Garay A, Iriarte LM, Armendia M, Marya S, Maître FL (2009) Machinability of titanium alloys (ti6al4v and ti555.3). J Mater Process Technol 209(5):2223–2230
2. Naidolny K, Sienicki W, Wojtewicz M (2015) The effect upon the grinding wheel active surface condition when impregnating with non-metallic elements during internal cylindrical grinding of titanium. Arch Civ Mech Eng 15(1):71–86
3. Zhang Z, Tong J, Zhao J, Jiao F, Zai P, Liu Z (2021) Experimen-tal study on surface residual stress of titanium alloy curved thin-walled parts by ultrasonic longitudinal-torsional composite milling. Int J Adv Manuf Technol 115(4):1021–1035
4. Davim JP (2014) Machining of titanium alloys. Materials Forming, Machining and Tribology Series, Springer
5. Pramanik A (2014) Problems and solutions in machining of tita-nium alloys. Int J Adv Manuf Technol 70(5–8):919–928
6. Dearney PA, Grearson AN (1986) Evaluation of principal wear mechanisms of cemented carbides and ceramics used for machining titanium alloy IMI 318. Met Sci J 2(1):47–58
7. Davim JP (2012) Machining of complex sculptured surfaces. Springer, London
8. Soe YH, Tanabe I, Iyama T, Cruz JRD (2012) Estimation tool for optimum cutting condition of difficult to cut materials. J Mach Eng 12(1):76–88
9. Shan ZD, Qin SY, Liu LF (2012) Key manufacturing technology & equipment for energy saving and emissions reduction in mechanical equipment industry. Int J Precis Eng Manuf 13(7):1095–1100
10. Ezugwu EO, Wang ZM (1997) Titanium alloys and their machinability—a review. J Mater Process Technol 68(3):262–274
11. Kumar U, Senthil P (2020) Performance of cryogenic treated multi-layer coated WC insert in terms of machinability on titanium alloys Ti-6Al-4V in dry turning. Mater Today: Proc 27(3):2329–2333
12. Rahman M, Wong YS (2003) Zareena AR, Machinability of tita-nium alloys. JSME Int J 46(1):107–115
13. Lacalle L, Perez J, Llorente JJ et al (2000) Advanced cutting conditions for the milling of aeronautical alloys. J Mater Process Technol 100(1–3):1–11
14. Kotkunde N, De Ole AD, Gupta AK, Singh SK (2014) Comparative study of constitutive modeling for ti-6al–4v alloy at low strain rates and elevated temperatures. Mater Des 55:999–1005
15. Kanna N, Davim JP (2015) Design-of-experiments application in machining titanium alloys for aerospace structural components. Measurement 61:280–290
16. Polini R, Barletta M (2008) On the use of cm/cr and crn interlayers in hot filament chemical vapour deposition (hc-cvd) of diamond films onto wc-co substrates. Diam Relat Mater 17(3):325–335
17. Deng JX, Li YS, Song WL (2008) Diffusion wear in dry cutting of Ti–6Al–4V with WC/Co carbide tools. Wear 265(11):1776–1783
18. Venugopal KA, Paul S, Chattopadhyay AB (2007) Growth of tool wear in turning of Ti–6Al–4V alloy under cryogenic cooling. Wear 262(9):1071–1078
19. Prengel HG, Jindal PC, Wendt KH, Santhanam AT, Hegde PL, Penich RM (2001) A new class of high performance PVD coatings for carbide cutting tools. Surf Coat Technol 139(1):25–34
20. Tönshoff HK, Mohfeld A (1998) Surface treatment of cutting tool substrates. Int J Mach Tools Manuf 38(5):469–476
21. Jiang F, Li Q, Leng YX, Huang N (2012) Wear mechanisms during sliding of ti64 balls against bare and hfcvd polycrystalline-diamond-coated wc-co exchangeable inserts. IEEE Trans Plasma Sci 40(7):1829–1836
22. Leksycki K, Królczczyk JB (2020) Comparative assessment of the surface topography for different optical profilometry techniques after dry turning of Ti6Al4V titanium alloy. Measurement 169:1–11
23. Tan L, Zhang D, Yao C, Ren J (2015) Influence of tool geometrical parameters on milling force and surface integrity in milling titanium alloy. China Mechanical Engineering 26(6):737–742
24. Quintanaa G, Ciurana J (2011) Chatter in machining processes: a review. Int J Mach Tools Manuf 51(5):363–376
25. Zacharia K, Krishnakumar P (2020) Chatter prediction in high speed machining of titanium alloy (Ti-6Al-4V) using machine learning techniques. Mater Today: Proc 24(2):350–358
26. Rafał R, Paweł L, Krzysztof K, Bogdan K, Jerzy W (2015) Chatter identification methods on the basis of time series measured during titanium superalloy milling. Int J Mech Sci 99:196–207
27. Hong SY, Markus I, Jeong WC (2001) New cooling approach and tool life improvement in cryogenic machining of titanium alloy Ti-6Al-4V. Int J Mach Tools Manuf 41(15):2245–2260
28. Davoodi B, Taze Khondi AH (2014) Experimental investigation and optimization of cutting parameters in dry and wet machining.
of aluminum alloy 5083 in order to remove cutting fluid. J Clean Prod 68:234–242
29. Niketh S, Samuel GL (2017) Surface texturing for tribology enhancement and its application on drill tool for the sustainable machining of titanium alloy. J Clean Prod 167:253–270
30. Maruda RW, Krolczyk GM, Nieslony P, Wojciechowski S, Michalski M, Legutko S (2016) The influence of the cooling conditions on the cutting tool wear and the chip formation mechanism. J Manuf Process 24:107–115
31. Sharma VS, Dogra M, Suri NM (2009) Cooling techniques for improved productivity in turning. Int J Mach Tools Manuf 49(6):435–453
32. Nandy AK, Gowrishankar MC, Paul S (2009) Some studies on high-pressure cooling in turning of Ti–6Al–4V. Int J Mach Tools Manuf 49(2):82–198
33. Tan RK, Zhao XS, Guo SS, Zou XC, Yang H, Geng YQ, Hu ZJ, Sun T (2020) Sustainable production of dry-ultra-precision machining of Ti–6Al–4V alloy using PCD tool under ultrasonic elliptical vibration-assisted cutting. J Clean Prod 248:119–254
34. Zhao ZA, Ts A, Zhu ZB, Yin TA (2020) A theoretical and experimental investigation of cutting forces and spring back behaviour of Ti6Al4V alloy in ultraprecision machining of microgrooves. Int J Mech Sci 169:1–11
35. Schaal N, Kuster F, Wegener K (2015) Springback in metal cutting with high cutting speeds. Procedia CIRP 31:24–28
36. Sutton MA, Orteu JJ, Schreier HW (2009) Image correlation for shape, motion and deformation measurements. Springer
37. Wang YH, Jiang JH, Wannirudal C, Du C, Zhou D, Smith LM, Yang LX (2010) Whole field sheet-metal tensile test using digital image correlation. Exp Tech 34(2):54–59
38. Wu DJ, Mao W, Zhou Y, Lu C (2011) Digital image correlation approach to cracking and decohesion in a brittle coating/ductile substrate system. Appl Surf Sci 257(14):6040–6043
39. Zhu J, Xie H, Hu Z, Chen P, Zhang Q (2011) Residual stress in thermal spray coatings measured by curvature based on 3D digital image correlation technique. Surf Coat Technol 206(6):1396–1402
40. Li DY, Huang PY, Guo XY, Zheng XH, Lin JX, Chen ZB (2018) Fatigue crack propagation behavior of RC beams strengthened with CFRP under cyclic bending loads. Fatigue Fract Eng Mater Struct 41(1):212–222

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