Online Measurement of the Elastic Recovery Value of Machined Surface in Milling Titanium Alloy

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Research Article

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Abstract

In the machining of titanium alloy, the elastic recovery of the machined surface will cause strong friction between the tool flank and the workpiece surface, which will result in the tool wear and the poor machined surface. This paper designed a new online measuring system to monitor the elastic recovery behavior of Ti6Al4V alloy in dry milling based on the digital image correlation (DIC). DIC measurement principle were analyzed and the orthogonal milling experiments were carried out under different cutting conditions. Because of the complexity of metal cutting environment such as high temperature and chip splash, and the micro scale of elastic recovery of metal machined surface materials, DIC non-contact sensor was designed to measure the deformation of machined surface materials in titanium alloy milling. The displacement data obtained from the experiment were analyzed, and the calculation method of the elastic recovery value of the machined surface was obtained. The measured data were compared with those in other literature. The focus of this paper is to explore the availability of DIC measuring instrument for measurement of elastic recovery in titanium alloy milling. This method can be extended to the measurement of machining of other difficult machining materials.

1 Introduction

Titanium alloys have been widely used in many fields such as aerospace industry because of their excellent features such as high specific strength (strength-to-weight ratio), good stability at high temperatures, high resistance to fatigue and creep, excellent corrosion resistance, etc. [1, 2]. Titanium alloys are mainly used in aircraft engine compressor parts, followed by rocket, missile and high-speed aircraft structural parts. So the machining of titanium alloys has always been a topic of great interest for industrial production. However, as shown in Fig. 1, the titanium alloys are regarded as one of difficult to machine materials because of the following characteristics [3, 4]:

(1) The higher hardness

Compared with light metal materials such as aluminum alloy, titanium alloy material needs more cutting force due to higher hardness. In fact, the cutting force in machining titanium alloy is only slightly higher than that of steel with the same hardness, but the pressure and local temperature are relatively high due to the small contact surface between the chip and the tool. Consequently, it is easy to cause tool wear and even damage of the tool tip or blade [5].

1. The lower elastic modulus E [6, 7]

Because of the lower elastic modulus and high yield strength, the volume of workpiece material in the vicinity of the machined surface undergoes excessive elastic deformation during machining. Consequently, it is easy to cause the dimensional error of machined parts, but also cause severe friction between the tool flank and the workpiece, resulting in tool wear and poor surface quality.

(3) The 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 [8, 9], which in turn results high temperature of the tool and lost its mechanical strength and hardness, and finally shortens tool life [10].

(4) Small deformation coefficient

Their deformation coefficient is 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 in the process of walking on the rake face.

(5) high chemical activity [11].

Titanium alloys have high chemical activity especially in high temperature environment. In the process of machining, it is easy to provide strong adhesion of workpiece material over the tool edge [12, 13], and it is also easy to react with the gas in the air, thus accelerating tool wear and leading to edge breakage [14].

In summary, the poor machinability of titanium alloys is due to their unique combination of the above five characteristics [15]. Rapid tool wear and poor machined surface quality are the main factors restricting the efficient machining of titanium alloy. Active chemical reactivity, severe friction and the elastic recovery of the machined surface are the main factors causing the poor machinability of titanium alloy, and these factors are interrelated to each other. For example, high cutting temperature promotes the chemical reaction, and decreases the elastic modulus of titanium alloys [16]. In addition, the cutting vibration caused by sawtooth chip produced in machining results in poor machinability of titanium alloy.

From the above analysis, it can be seen that the high-speed cutting of titanium alloy is limited because of its poor characteristics. The research on improving the machinability of titanium alloy mainly includes the following aspects:

Reasonable selection of tool base materials and coating materials is an effective way to reduce the diffusion and chemical reaction between the tool and the workpiece [17]. WC-Co carbide is regarded as the most suitable tool material available commercially for the machining of titanium alloys [18, 19]. However, WC-Co tools wear rapidly in machining titanium alloys, particularly at high cutting speed [20]. Nowadays, most of the carbide tools are coated with CVD (Chemical Vapor Deposition) or PVD (Physical Vapor Deposition) hard coatings to resist tools wear [21, 22], and CVD diamond-coated carbide tools are a promising choice for machining titanium alloys [23]. Optimization of tool structure and cutting parameters can effectively improve the machinability of titanium alloy [24]. The tool structure has a considerable influence on the machined surface integrity [25]. It is proposed to use non-standard tool, namely variable pitch tool, to reduce cutting vibration by destroying regeneration effect [26], correspondingly decrease cutting temperature and tool wear. Stability lobe diagram that is plotted between spindle speed and depth of cut often is used to select the proper cutting parameters to avoid cutting chatter [27, 28]. Usage of cutting fluids has traditionally been used to reduce the temperature developed during machining and improves the tool life [29]. However, there will be negative effects such as environmental pollution and hazards to operators due to the excessive use of cooling/lubricating fluids [30]. Moreover, the cost of preservation, maintenance and disposal of these fluids is much more expensive than its purchase price, which greatly increases the total manufacturing cost [31]. Various cooling and lubrication techniques in the cutting zone have been developed, such as MQL (Minimum Quantity Lubrication) [32], cryogenic machining [33], and HPC (High Pressure Cooling) [34]. Dry machining eliminates cutting fluids, and it is therefore considered an environmentally friendly and sustainable machining strategy [35].

It can be seen from the above literature that although the elastic recovery of titanium alloy during machining is large, which limits its high-speed cutting, little attention has been paid to its measurement. The reason may be due to the complexity of titanium alloy cutting environment, and the most important reason is its micro scale. In a few literatures, Zhao [36] developed the material constitutive models and geometrical relationships about Ti6Al4V alloy to estimate the temperature evolution, cutting forces, internals force/stress distribution and the spring back variation during micro groove turning. Through theoretical and experimental analysis, it is concluded that more than 45% of the thrust comes from the spring back. Schaal [37] designed an online measuring system for the elastic recovery of turning aluminum alloy and titanium alloy. The elastic recovery measuring system consists of 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 will inevitably produce measurement error due to the influence of installation accuracy, tool vibration and surface roughness difference before and after the cut. So it is very important to develop new high-precision measurement methods.

In this paper, it is studied that an online measurement of the 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 for the purpose of suppressing 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 fields due to its simple optical path, good environmental adaptability, wide measurement range and high degree of automation welding and many other scientific and engineering fields [38]. The most widely and mature application of DIC technology in material research is to use DIC technology instead of extensometer to measure the real-time strain of the sample in the tensile process [39]. Wu et al. use the 2D-DIC technique to monitor the full/local field strain in both coating and substrate systems [40]. Zhu 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 [41]. Li carried out the fracture analysis of concrete to ensure the relative position of the camera and the specimen plane by 3D-DIC technology [42].

Combined with the measurement characteristics of DIC, this paper introduces 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 section 2. In section 3, experiment process and results were presented in section 3. And finally, the conclusions are draw in section 4.

2 Online Measurement Of The Elastic Recovery Of Machined Surface

The elastic recovery of the machined surface belongs to micro scale, and considering the poor cutting environment, it is not suitable for direct contact measurement. In this paper, DIC optical non-contact method was used to measure the elastic recovery.

2.1 DIC measurement principle

The measurement principle of DIC is to use two cameras to capture the speckle image of object surface from different angles, match the overlapping areas in the images taken by the two cameras, and use the camera calibration parameters to determine the three-dimensional coordinates of each point on the object surface in the overlapping area, so as to realize the three-dimensional morphology and deformation measurement. Fig. 2 (a) shows the tested part before deformation, and Fig. 2 (b) shows the tested part after deformation under the action of load P. Their corresponding the speckle image are defined as the reference subset and the target subset. The measurement method of DIC is making a correlation between two images taken before and after loading the tested part, and finally calculate the displacement distribution of the whole tested part in the discrete space.

2.2 Experimental conditions and experimental steps

Figure 3 (a) and (b) show the schematic picture and actual picture of the experimental 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 a AlCrN coating was selected, and its geometric parameters are as follows: tooth number N is 4, diameter D is 20 mm, overhang length l is 42mm and helix angle β is 38°.

PMLAB DIC-3D was used to monitor the elastic recovery of machined surface. The measuring system consists of a non-contact 3D displacement measurement software, a PM-G universal measuring head including 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 13fps. KOWA industrial lens has an aperture of 2.0, a focal length of 28mm, and an aperture of 1.3 inch. Measurement range of the system: large field of view > 1m ×1m, and maximum measurement points of 20000.

The speckle image of the object surface is shown in Fig. 3(c). Before painting, it is necessary to ensure that the surface of the test part is smooth and free from oil stains. In order to ensure 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, a point is required to occupy 4-6 image pixels.

After the installation of the experimental device, the test site must be calibrated as shown in Fig. 4.

Firstly, open the camera cover and put the camera in a suitable position, so that 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. 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.

After calibration, turn on the camera and select binocular camera for acquisition. The acquisition time is 150s, 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

In order to study the influence of milling parameters on the elastic recovery of Ti6Al4V alloy during dry milling. Multi-factor orthogonal design method was used 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 1000-1500mm from 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, and so it is 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.

Table 1
Factors and levels of orthogonal test

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

3 Experiment Process 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 process

As Fig. 5, in the 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 standard for selecting this subset is that it is relatively close to the machined surface, which can reflect the elastic recovery value of the machined surface more accurately.

Figure 5 (a) shows the schematic diagram of different cutting positions of the tool and the deformation of the target subset of the tested part. Figure 5(b) shows 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 ordinate is the displacement in *y* direction of the target subset. The cutting time of the tool is 147.8s.

When the tool passes through the top of the target subset for about 8 seconds, 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 sub region is equal to that of the machined surface. In the process of the tool feed process, the cutting load *P* is gradually approaching the target subset, the displacement curve shows a downward trend. A negative sign indicates that the displacement of the machined surface changes downward, and the greater the absolute value is, the greater the displacement change is.

As shown as Fig. 5(c), affected by cutting force and cutting vibration, the whole curve has some fluctuation, and 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. Here, it's represented by the letter δ. Reading time of the elastic recovery value is set to 140 seconds - 148 seconds.

3.2 Experiment results

Figure 6 shows the *y*-direction displacement curve of 16 groups experiments within the given 8 seconds. As can be seen from the figure, it can be seen from each group of data that the compression of the target subset materials when the load reaches and the elastic recovery trend when the load leaves.

According to 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.

Table 2
Measured values under different cutting conditions

Number	n	a_p	f	δ(um)	Number	n	a_p	f	δ(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

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

Figure 7 (b) 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 1.7325μm, 0.8875μm and 0.2025μm, respectively. Therefore, from reducing the elastic recovery value, if you want to increase the material removal rate (such as rough machining), you can consider increasing the feed rate per tooth, and then consider increasing the axial cutting depth.

In reference [36], in the process of micro groove cutting of Ti6Al4V alloy, the elastic recovery value is between 0.9-1.1μm. In reference [37], when the cutting parameters of Ti6Al4V alloy are, cutting depth a_p=0.05mm, feed rate f=0.1mm/rec, cutting speed v=10-450m/min, the elastic recovery values are between 0.3-1.6μm with a sharp tool (cutting edge radius 12 μm); the values are between 2.1 and 9.6 μm with a blunt tool (cutting edge radius 72 μm). In this paper, the values are between 2.69-5.46μm during milling Ti6Al4V alloy.

4 Conclusion

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

(4). Compared with the range of elastic recovery measured in the previous references, it can indirectly verify the effectiveness of the method used in this paper.

Declarations

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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Data Availability Not applicable

Code availability Not applicable

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

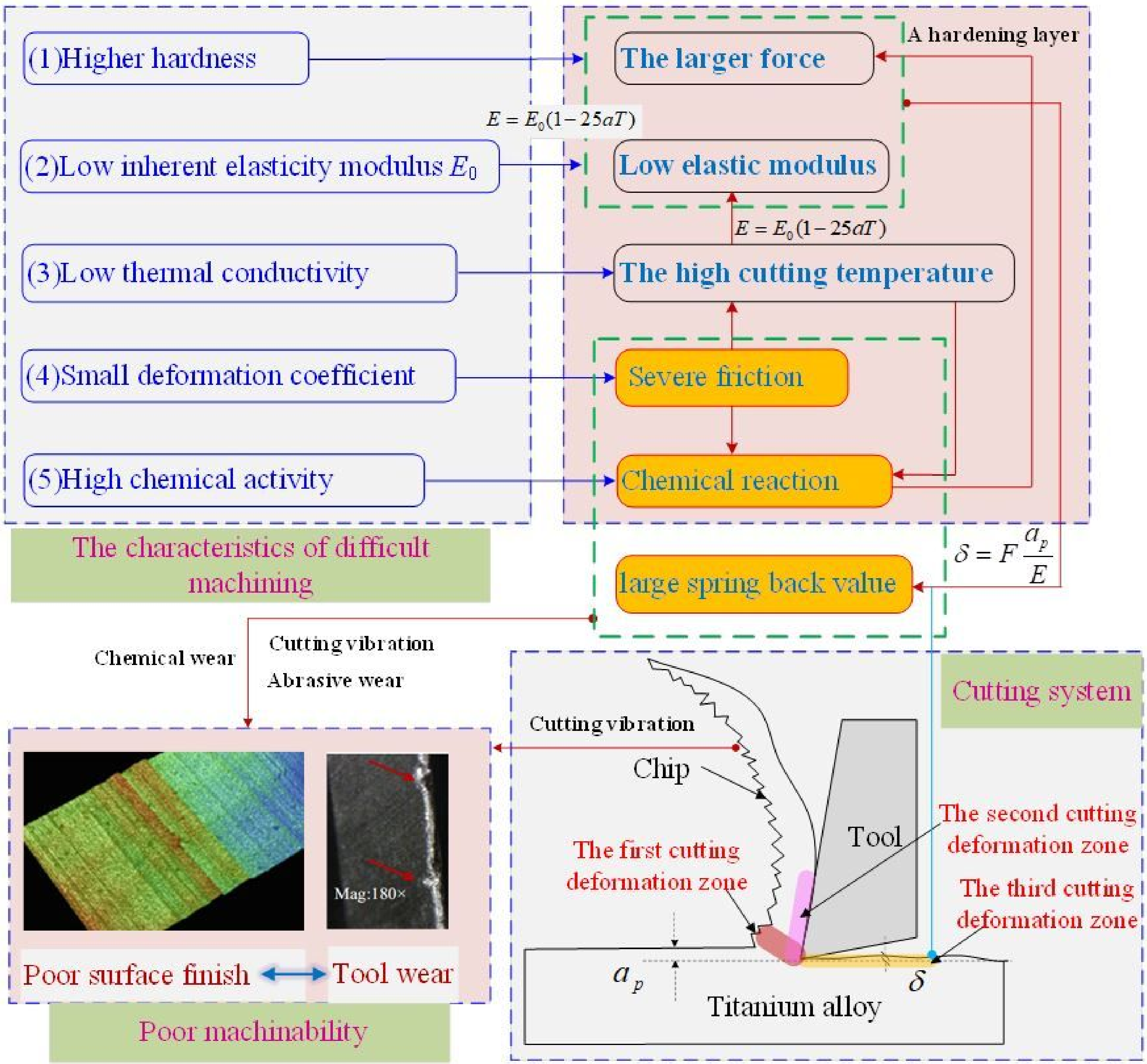

Figure 1

Poor machinability of titanium alloy

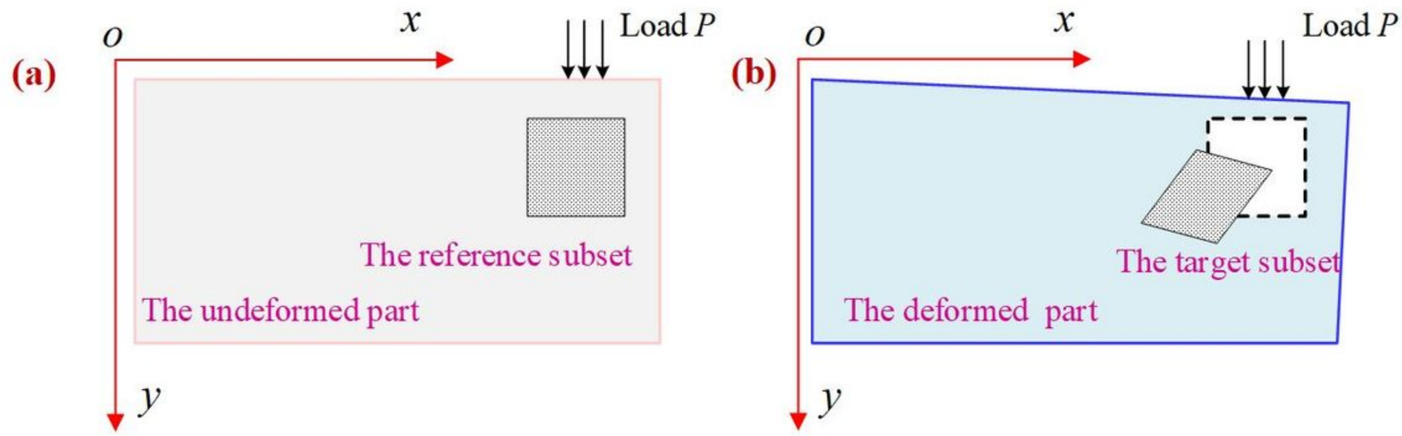

Figure 2

The measurement principle of DIC

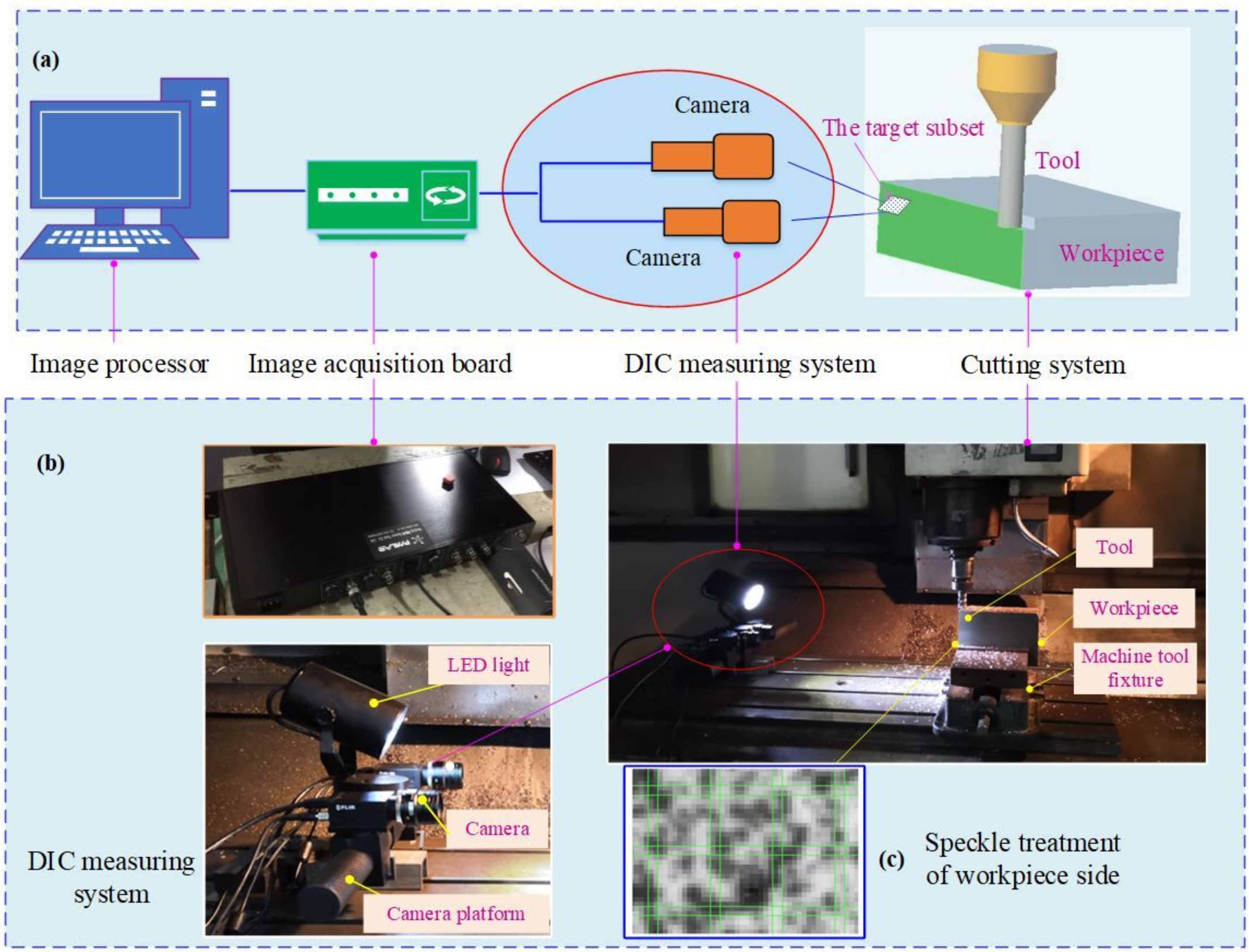

Figure 3

Experimental setup

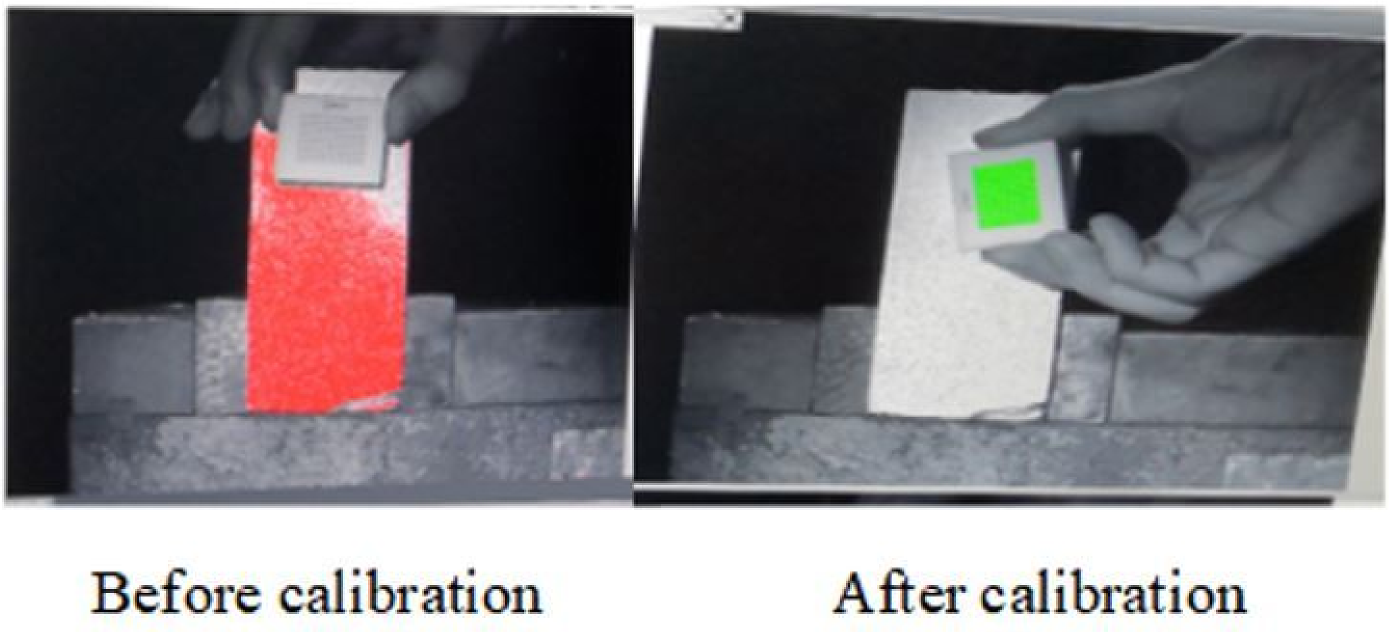

Figure 4

The test site calibration

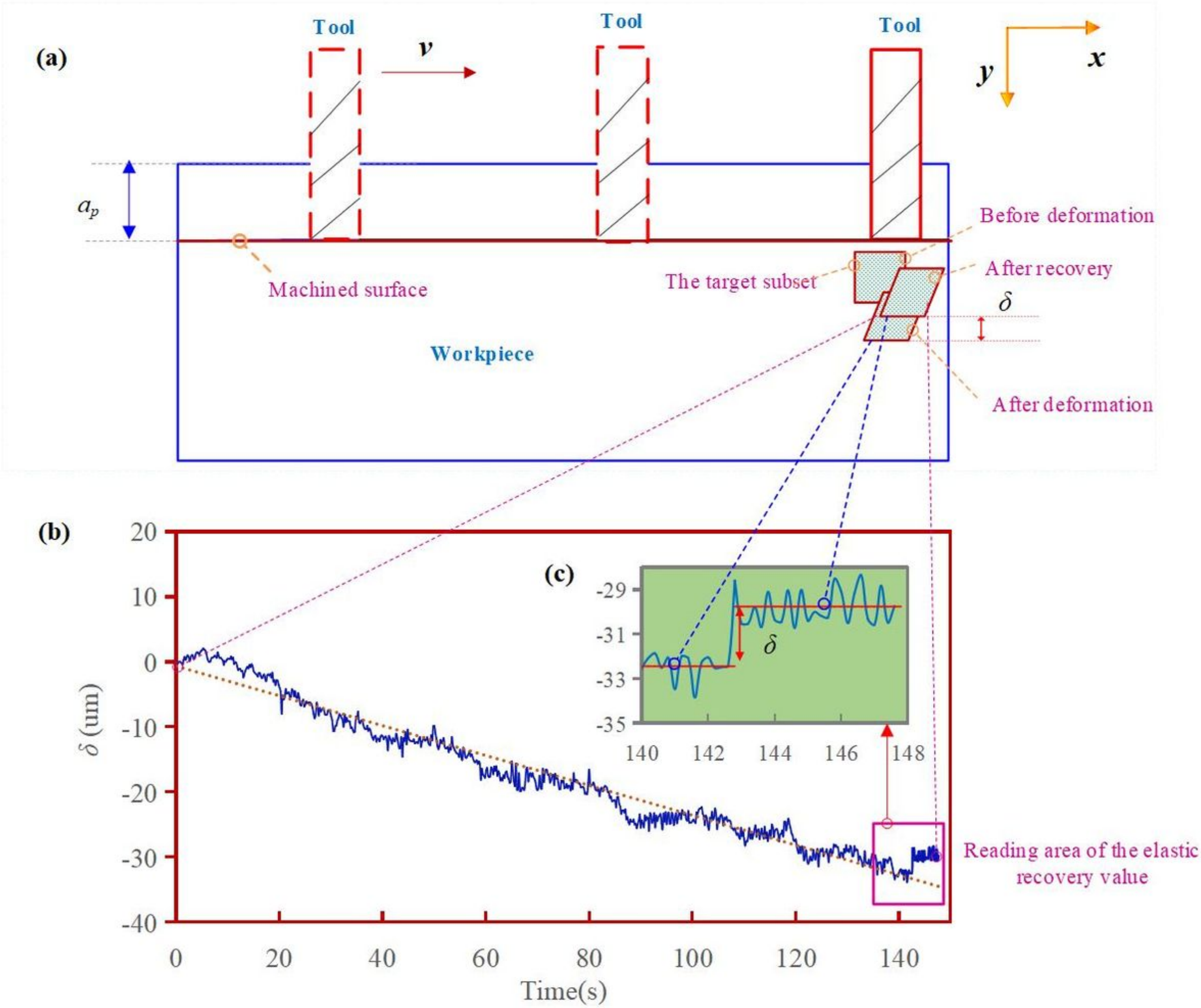

Figure 5

Real time displacement change

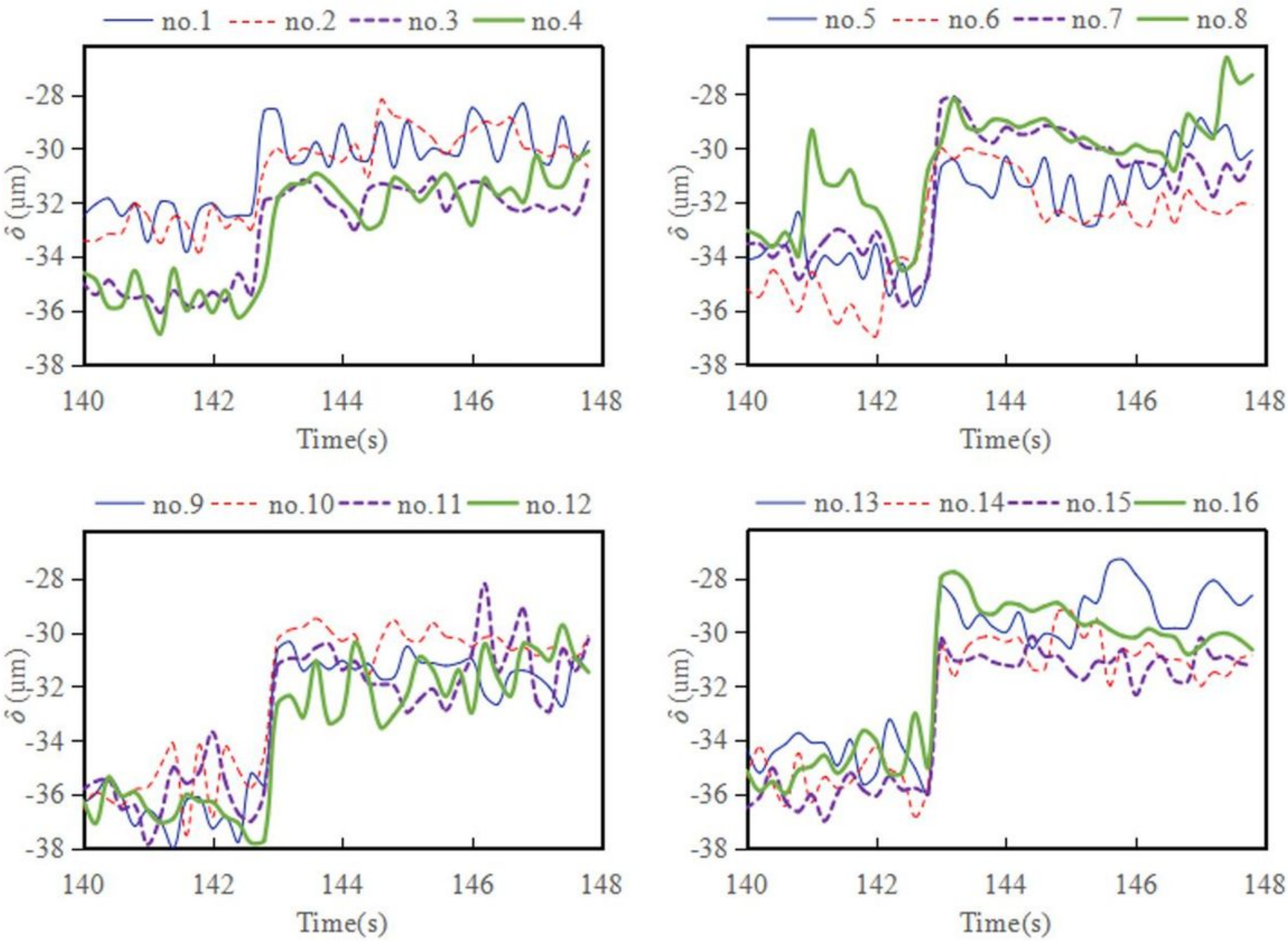

Figure 6

The elastic recovery curves of orthogonal experiments

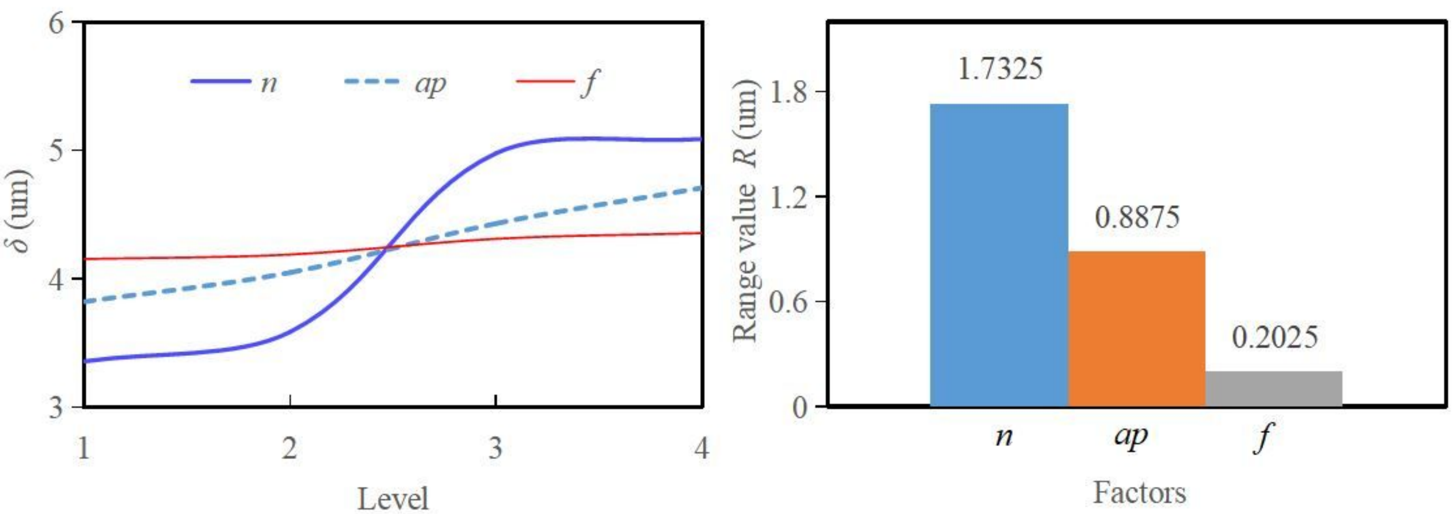

Figure 7

Range analysis