Precision Engineering 47 (2017) 81–89

Contents lists available at ScienceDirect

Precision Engineering

journal homepage: www.elsevier.com/locate/precision

Effect of downward depth and inflation pressure on contact force of gasbag polishing

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ARTICLE INFO

Article history:
Received 22 January 2015
Received in revised form 28 June 2016
Accepted 12 July 2016
Available online 27 July 2016

Keywords:
Gasbag polishing
Contact force
Control system
Surface quality

ABSTRACT

Gasbag polishing is a kind of ultra-precision machining technology by means of flexible contact, while how to control the polishing contact force online is one of the key issues. In this paper, by analyzing the effect of downward depth and inflation pressure on the contact force experimentally, and then the coupling contact force model is developed. Thus, the predictions of polishing contact force and inflation pressure in terms of the nonlinear composite material of rubber gasbag can be obtained, which can be used to get the optional combination and controllable range of polishing contact force, and to construct the control system of coupling contact force as well. Experimental study shows that applying coupling contact force model to the control system of gasbag polishing contact force with BP neural network PID control strategy is a proper method, which realizes the polishing contact force controllable online and uniform surface quality of mold.

1. Introduction

Abrasive machining technology is widely used in the precision engineering via the erosion between the abrasive particles and workpiece, such as abrasive jet micro-machining [1], high speed grinding [2] and fixed abrasive lapping [3]. To polish the free-form surface of mold using gasbag polishing technique is a novel method, which uses the abrasive embedded in the gasbag to achieve the material removal and has good compliance and fits to the free-form parts [4]. The flexible gasbag with certain inflation pressure is used as a polishing tool, which can be attached on the surface of the mold tightly. Therefore, the gasbag polishing is applicable to the processing of free-form parts. The contact force of gasbag polishing is generated by directly contacting between the gasbag and mold surface, which is associated with material properties, structure, size, downward depth and inflation pressure of gasbag and would affect the polishing efficiency and quality due to the induced different erosion modes between the abrasive particles and the target [5]. For the same type of gasbag with the certain material properties, structure and size, the contact force can be controlled by the downward depth and inflation pressure [6].

The methods for controlling the contact force can be roughly divided into two modes, i.e. the rigid and flexible contact force control modes [7]. In the rigid contact force control mode, the contact force is controlled by a motion control system, which is subjected to the response time and resolutions of the motion control system. Fusaomi et al. first experimentally examined the resolution of position and force, and effective stiffness using an automatic polishing system according to an articulated 6-dof industrial robot [8,9]. Kamezaki et al. established online constant force control system with 6-axis force sensor, and applied fuzzy theory to control the movement of the polishing robot [10]. Chen et al. proposed a real-time feedback function on the feed-rate of the milling tool by load-cells devised on 3-axis CNC machine tool, which can improve the surface quality of quartz-glass effectively [11]. All the above mentioned methods belong to the rigid contact force control mode, and in general the performance of the machining quality mainly depends on the resolutions of the motion control system.

In the flexible contact force control mode, the contact force is provided by an independent control mechanism. Thus, the pose and contact force of the polishing tool can be controlled respectively. Flexible contact force control modes can be divided into passive and active flexible contact force control. Yu et al. developed an automatic grinding and polishing tool with elastic material in the base part [12]. Liu et al. investigated the polishing of molds and dies using a compliance tool holder mechanism to reduce the variation of polishing force, and it was found that imposing compliance in the tool

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http://dx.doi.org/10.1016/j.precisioneng.2016.07.007

holder can reduce surface roughness and variation of the polishing force [13]. Chaves-Jacob et al. used a flexible tool to obtain a smooth connection between contact force and tool position due to the fact that CNC machines can be used to control the position ratehr than the froce, which could reduce the tool wear and stabilise the radial force applied during the pre-polishing process [14]. Mizugaki et al. presented a new metal-mold polishing robot system with a compliant polishing end-effector, and the experimental results support the efficiency of the contact pressure control path as to preventing over-polishing at an edge [15]. These findings belong to the passive flexible contact force control mode. While the contact force of active flexible contact force control mode is regulated by sensor, control system and end effector. It is more flexible and accurate than passive flexible contact force control mode. An adaptive controller was developed by Liao et al. to obtain the pressure tracking of the pressurized tool-head by using an active pneumatic compliant tool-head, which is proven to be effective and can be directly applied to the pressure tracking control through self-tuning [16]. Shi et al. proposed a force control subsystem based on a magneto rheological torque servo to provide a controllable torque to polishing tool to generate and control the polishing force, where a PID controller was also designed for torque tracking with the actual torque feedback from a torque sensor. It was although common PID controller in this study can deal with this problem, a more effective control algorithms need to be studied in the future [17]. Guo et al. proposed to precisely control polishing force in real-time for the first time, and a simple mechanism consisting of a load cell, a piezo stage and a linear stage was also proposed. The results indicate that this method enables a stable polishing force with a high resolution [18]. Kakinuma et al. proposed a novel methodology based on the sensor-less force control technique and the quarry matrix capable of the mode decoupling for a parallel mechanism polishing machine in order to control x-y trajectory, tool posture, and polishing force in z direction, such that through input of a tool path, polishing force, and tool posture equivalent to those for actual polishing by a skilled worker, the resin workpiece used for coating can be evenly polished [19]. These discussions belong to the active flexible contact force control mode. According to the above-mentioned analysis, the active flexible control force mode presents more advantages in controlling the contract force than other methods with high efficiency and resolution. Thus, in this paper an active flexible contact force control mode was selected to control the contract force with respect to the internal inflation pressure and the downward depth.

The adjustment of internal inflation pressure of rubber gasbag and control of 6-dof robot are independent with each other, thus a steady contact force can be achieved by regulating the inflation pressure of gasbag. In this paper, a model to predicting the coupling contact force with respect to the downward depth and inflation pressure is developed according to the experimental results. Then, the adjustable range of polishing contact force can be obtained and the online monitoring and control system of polishing contact force is then constructed. Finally, the correctness of coupling contact force model and the effectiveness of contact force control system are validated experimentally.

2. Model of gasbag polishing coupling contact force

A schematic illustration of the gasbag polishing tool is shown in Fig. 1. A gasbag polishing tool rotates around the P axis with a rotation speed of ω_1, and it also has a revolution movement around the N axis with a speed of ω_2, in which θ is defined as the angle between the P axis and N axis. At the same time the gasbag polishing tool is connected with a robot machine to realize its movement along the workpiece with a speed of v as shown in Fig. 1(a). In addition, the detail of the contact area of the gasbag polishing tool with the workpiece is shown in Fig. 1(b), in which the contact area is defined as the circle area with the diameter of S, and h is the downward depth. At the inflation pressure of zero, the gasbag will be forced downward by the robot until the force sensor on the workpiece changes, and in this location it is defined as $h = 0$. Therefore, with certain downward depth and inflation pressure of the gasbag the workpiece could be polished by means of the cutting action of abrasive particles between the gasbag and workpiece.

The polishing contact force is related to the downward depth and inflation pressure of the rubber gasbag during the gasbag polishing process. The downward depth of gasbag is controlled by the 6-dof robot and it is fluctuant due to the mold surface morphology and other processing parameters. Thus, the contact force should be adjusted by using inflation pressure of gasbag actively to offset the fluctuation of the downward depth. In the polishing process, the contact force plays an important role in the material removal process. The preliminary experiment indicates that dynamic normal contact force is similar to static normal contact force, so that the static contact force rather than the dynamic contact force was considered in this study in order to simplify the experiment process. The experimental study on obtaining the gasbag polishing contact force with respect to different downward depths and inflation pressures were conducted to develop the coupling contact force model and realize the online control of polishing contact force with the specific type of rubber gasbag.

Experimental analysis of gasbag polishing contact force (F_C) with respect to process parameters, including the downward depth and inflation pressure was first carried out. The downward depth (h) and inflation pressure (p) are input quantities, and contact force is output quantity. Thus, F_C can be expressed as a function of h and p, which is expressed as $F_C(h, p)$. This function is obtained from a large number of repetitive experiments to ensure its applicability for gasbag polishing process. The hemispherical rubber gasbag with diameter of 40 mm, wall thickness of 3 mm and shore hardness of 48A was selected as the polishing tool according to the preliminary experiments. The value of h was set ranging from 0 to 3 mm, while the value of p was set from 0 to 50 KPa in experiment. The experimental analysis result is shown in Fig. 2.

As shown in Fig. 2(a), under the combined conditions of h and p, F_C has a good monotonicity, and there is no obvious extreme point and small range ability. As shown in Fig. 2(b), the change of F_C is nonlinear, i.e. h and p have a coupling effects on the F_C. Thus, using different kinds of fitting methods to get the expressions of the predicting model can be used to verify that if the coupling effect exists or not. Some typical fitting methods including plane, exponential, biquadratic polynomial, coupled polynomial, dual coupled second order polynomial, higher order polynomial, dual coupled third order polynomial fitting were considered in this study.

A determined function $R^2_{adjusted}$ (characterization of fitting quality) was used to quantitatively evaluate the fitting effect, which is given by:

$$R^2_{adjusted} = 1 - \frac{m-1}{m-n-1}\frac{\sum(y_i-\hat{y})^2}{\sum(y_i-\bar{y})^2} \tag{1}$$

where $\hat{y}$ is the fitting value from the predicted model, y_i means the real experimental data, $\bar{y} = \frac{1}{m}\sum_{i=1}^{m} y_i$, m means the total number of experimental data, n means the number of basic functions, and $\frac{m-1}{m-n-1}$ means the real size of degree of freedom for $R^2_{adjusted}$. The bigger value of $R^2_{adjusted}$ is, the better fitting quality of the fitting method would be.

Based on least square method, the experiment data was analyzed by various fitting methods, and the corresponding results are shown in Table 1. The plane fitting method results in a big error,